TUNING FORK PRECISION OSCILLATORS

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SUMMARY

The performance characteristics and certain design considerations of tuning fork resonators and associated oscillator circuits are discussed. Historical development of the tuning fork oscillator and its applications are briefly outlined. Fabrication methods and mechanical configuration of units at frequencies in the complete audio range are shown. Effects of environment are discussed. This includes effects of temperature, atmosphere, positioning, and mounting, vibration and shock, aging, and the relation of these to fork frequency.

Methods of temperature compensation including bi-metallic and mono-metallic construction are presented for comparison, and physical environmental effects on temperature coefficient are given.

The fork resonator and coupling assembly is shown as an equivalent two port network and its use with various active elements is described. Discussion of both transistor and vacuum tube circuits is presented and the relation of the circuit to resonator Q and temperature coefficient is outlined.

Presently obtainable accuracies as well as those ultimately obtainable are given.

INTRODUCTION

The tuning fork has been utilized in the field of physics, primarily in the study of sound, since early in the 19th century. One of the early investigators, W. R. Koenig[1] originated the electrically driven fork. While the fork has been with us longer than the quartz crystal, the crystal has received considerably more development for electronic applications. This is true because the initial need in communications was for frequency control of transmitted carriers. Today, with the special requirements for control in the audio frequency range for instrument and computer applications, the tuning fork and associated oscillator circuits are receiving considerable attention and require considerably more to fulfill their potential.

With the advent of electronic circuitry and the development of a "constant modulus alloy" by Guilliame[2], a stable frequency source in the audio range was available to the industry. Another important step was the development of the laminated fork[3] formed by bonding together two different metals to achieve a reduced temperature effect.

The tuning fork as a classroom device to demonstrate sound is well known. Its use as a precision frequency source is also well known. Developmental emphasis is on improving the accuracy and stability of this device as related to environmental conditions. The tuning fork as a narrow band filter has not been widely used although its potential is great for this application. Much work needs to be done on the latter two of these applications to demonstrate the tuning fork's best capabilities.

The tuning fork as an audio frequency signal generator has certain advantages not inherent in other devices. It will operate over a wide range of temperature. The limits are determined by the circuit components used and the Curie point of the fork metals. Operation of a tuning fork oscillator as high as 200°C and as low as -90°C has been investigated by the authors. The tuning fork is a rugged device and has no limitations in length of life. Tuning forks have been running continuously for ten years or more, with slight adjustments for aging and circuit parameter effects being the only attention needed. They can be made reasonably small and still maintain a degree of resistance to vibration and shock effects. Any discreet frequency may be had directly by proper dimensioning of the fork tines. The circuitry associated with the tuning fork as an oscillator may be extremely simple as will be shown later.

FORK RESONATOR CHARACTERISTICS

One method used to explain the mode of vibration of a fork is that used in most sophomore physics texts. This explanation shows a bar in flexural vibration, bent such that the two node points move closer together until when a complete fork is formed, the node points are located at opposite sides of the fork crotch. This effectively eliminates the distance between the node. Typical fork configurations are shown in Figure 1 for commonly used frequencies.

Most tuning forks are made with straight tines because of the simplicity of fabrication and the ease of calculating the dimensions for a particular frequency. The type with the holes or cutouts at the crotch will provide a lower frequency for a given length by maintaining a relatively large mass.

The fork frequency may be calculated by the following empirical formula: (1)

$$F = K \left(\frac{Ym}{D}\right)^{\frac{1}{2}} \frac{W}{L^2}$$

F = Frequency
K = Shape Factor
Ym = Young's Modulus
W = Width of tines
L = Length of tines

The thickness and width of the overall fork affect the frequency only slightly (a few hundred parts in a million). Typical tine dimensions as a function of frequency are shown in the following table. A fork of any frequency can be made longer or shorter by proper proportioning of the other dimensions.

Frequency	Length of Tine	Thickness of Tine	Width of Fork
400	1.625"	0.033"	0.375"
1000	1.625"	0.085"	0.375"
1000	2.250"	0.180"	0.600"
5000	0.080"	0.115"	0.375"

A tuning fork does not generate large amplitude harmonics of the fundamental, as is popularly believed. The harmonic content present is largely due to nonlinearities of the circuitry associated with the fork as in any self limited oscillator. There are, however, two overtones, at $6\frac{1}{4}$ and 17-1/8 times the fundamental frequency. These are sometimes referred to as the "clang tones" of the fork and contribute to the initial sound heard when the fork is mechanically excited.

Of prime importance is the shape factor of the tuning fork. The larger the fork mass, the less susceptible it will be to driving system amplitude changes and to vibration and shock. Frequency shift with changes in attitude will be proportional to tine length at any given frequency. This factor is dependent on the width of the tine, the thinner the tine, the more variation in frequency can be expected with the condition stated above. Forks made to the dimensions indicated previously, which are a compromise between the advantages of large size and the need for a small package are the types considered here.

Temperature variation is the largest single factor affecting frequency stability. Equation (1) shows temperature affects to be due to the temperature coefficient of modulus of elasticity and the coefficient of linear expansion. By denoting (α) as the T.C. of the modulus of elasticity, and (γ) as the T.C. of linear expansion, and β the T.C. of frequency, the relation is as follows:

$$\beta = \frac{\alpha + \gamma}{2} \qquad (2)$$

By suitable selection of materials, the T.C. of frequency can be made to approach zero. This was the basis for development of the constant modulus alloys.

Another factor affecting frequency is the damping effects of the devices used to couple energy to the fork. A set of coils and associated magnets are normally used. The "gapping" of the "drive and pickup" coils (the spacing of the coils from the tines) and the amplitudes of the signal impressed on the "drive" coil, determines to a certain extent the frequency of operation and the temperature coefficient of the tuning fork oscillator.

The mechanical quality factor "Q" of the fork can be defined as

$$Q = \frac{WM}{R} \tag{3}$$

M = Mass (Equivalent mass of the vibrating portion of the tine)

R = Mechanical Resistance

$W = 2\pi f$

"Q" can be determined from the spacing of half power points or by the vibration decay characteristics.

Tuning forks operating in free air have been made with "Q" values approaching 10,000 - 15,000 and in an evacuated system as high as 25,000. The addition of the energy coupling devices will lower the effective "Q" of the fork to 5,000 - 10,000. These figures are to a great extent dependent on the type of circuit used.

Figure (2) shows a typical mounting assembly. Tuning and balancing of the fork in this position, provides for the least change in frequency with attitude changes. Typical magnitudes of this effect are listed below:

Vertical	0 PPM
Horizontal Side	0 - 10 PPM Depending on frequency
Horizontal Flat	1 - 2 PPM Depending on frequency

A 400 cycle fork will have a frequency shift of 6-10 PPM, while a 5000 cycle fork will shift frequency 1 PPM maximum.

Vibration and shock environments affect frequency quite radically. The following table shows the frequency deviation due to shock and vibration on the tuning fork and mounting assembly illustrated in Figure 2. No shock mount was used.

Frequency	Shock & Acceleration	Frequency change
400	15 G	.01%
1000	15 G	.0056%
	Vibration	
400	.5" to 20 cps - 10G up to 30% of Freq.	.01%
1000	.5" to 20 cps - 10G up to 30% of Freq.	.01%

The stress and strain developed in a fork, for example, by cold working can cause considerable frequency aging in a matter of days. The fork is heat treated after working to relieve the strains and improve aging characteristics.

Figure (3) shows a typical aging curve and the limits normally found in a number of forks that have undergone this treatment. Operation was at room ambient temperature. Aging will continue in the area prescribed with a continually decreasing rate. The frequency after a year, would not be more than several parts per million more than shown on the curve. The normal drift with time is in the direction of increasing frequency.

The frequency of a tuning fork will also be affected by variations in barometric pressure. Size of fork tines (a frequency factor) determine to a great extent the amount of change. The thinner the tine, the more the effect.

Decreasing the barometric pressure to the range of 100 microns, will increase the Q allowing the fork to run harder, and decrease the frequency by as much as 300 PPM at 400 cycles, for example. As the fork frequency increases, this effect of barometric pressure change decreases. By hermetically sealing or evacuating the fork package, frequency shift with barometric changes can be minimized.

TEMPERATURE COMPENSATION METHODS

The tuning forks used today as controlling elements of high precision oscillators utilize either a mono-metallic "Constant Modulus Alloy" or Bi-metallic construction.

The metal used for Mono-metallic types has an analysis in the range shown below.

30 to 38%	Nickel
5 to 13%	Chromium
48 to 61%	Iron
0.5 to 2%	Manganese
0.5 to 1%	Silicon
0.5 to 1%	Cobolt
1 to 3%	Tungsten

Fork manufacturers using this type of construction may vary the analysis to provide certain effects determined by their specific requirements including stability, temperature limits, etc.

Figure (4) shows a typical temperature coefficient curve. Initially, the curve is more parabolic, final temperature compensation of frequency being accomplished by heat treatment. This heat treatment procedure is dependent on the analysis of the metal used and the amount of cold working done.

The Bi-metallic type of construction shown in Figure 5 utilizes a block of Constant Modulus Alloy and a strip of carbon steel, silver soldered together. The ratio of nickel alloy to carbon strip thickness determines the temperature coefficient of the tuning fork. This ratio will be in the range of 4-5-6 to 1 with the nickel alloy being the largest quantity. The ratio is determined by the physical size of the fork and the final temperature coefficient desired for a specific accuracy of frequency. The temperature coefficient in free air is different from that when the fork is assembled with the magnets and drive coils. Therefore, the ratio of alloy to carbon steel is chosen for proper T.C. when assembled.

A greater thickness of carbon steel than finally required is utilized in initial fabrication to assure control over the final T.C. The initial T.C. is negative and a part of the production procedure is to check the T.C. and reduce it by grinding off a portion of the carbon strip. Usually this amount is .001" to .003" per one PPM of Frequency change per degree C. Figure (6) shows a typical T.C. curve and the change of T.C. with grinding.

The value of "Q" has a slight effect on the T.C. of a fork which is now under investigation.

Barometric pressure affects the T.C. of a fork. For example, if a tuning fork is made to have a Negative T.C. of 1 PPM per degree C, placing the fork in an evacuated system of 100 microns, will move the T.C. as much as 5 PPM per degree C Positive, for low frequencies (60 cps). This T.C. shift will be less as the frequency of the fork is increased.

Aging of the fork will also affect the T.C. The T.C. will normally move in a more Negative direction with time. The magnitude over a period of months is not more than 0.5 to 1.0 PPM.

The circuit, since it has the effect of lowering the effective "Q" of the fork, affects the T.C. of the complete assembly. This movement, depending on the frequency of the fork, may have a magnitude as high as 10 PPM and is normally in the positive direction.

Amplitude of driving signal will also determine the original circuit and fork T.C. Figure (7) shows this effect.

OSCILLATOR CIRCUITS

A simplified equivalent circuit of the fork assembly, in the form of a two terminal pair network, is shown in Figure (8). The fork is plagued with the same problems as a crystal in that the equivalent parameter values are dependent on amplitude of vibration. The representation shown is based on that of an electromagnetic or magnetostrictive transducer or resonator in which an output coupling is placed to produce an output proportional to the amplitude of oscillation. Transmittance (ratio of generalized output to input) as a function of frequency is shown. The peak response corresponds to antiresonance of the motional parameters as represented in the equivalent circuit shown.

The second response, which corresponds to series resonance of the motional equivalent capacity with the coupling coil inductance, is typically one or two percent higher in frequency than the primary response, depending on coupling coil Q. This second response is sufficiently low in amplitude in comparison to the main response so that oscillation does not occur at other than the primary response. Another factor not shown in the equivalent circuit is the mutual coupling between L_1 and L_2 which does exist and becomes quite apparent at the higher audio frequencies.

The active portion of a tuning fork oscillator consists simply of an amplifier, usually self limiting, having sufficient gain and proper phase relationships to start and maintain oscillation. The two terminal pair fork network as used has a phase reversal from input to output so that an additional reversal is required in the active portion of the circuit. The most common active devices used are vacuum tubes and transistors. A typical example of the circuit configuration of each is shown in Figure (9). Early electrically driven forks utilized an arrangement of carbon microphones as active pickup and drive element. Stabilizing elements such as thermistors and varistors are sometimes utilized to improve gain and amplitude stability with temperature changes and to improve limiting. Normally, however, satisfactory operation is maintained without the addition of these circuit elements. Bias and operating point stabilization design problems are the same as those inherent in any oscillator design. An important design consideration is phase stability of the driving circuit. This is best accomplished by designing the circuit for broadband operation. Then the fork is the only frequency controlling element. Circuit gain is adjusted so that sufficient loop gain does not exist unless the fork is in motion but is sufficiently high to allow oscillation to start in a reasonable period of time.

CONCLUSIONS

Present day accuracies of tuning fork oscillators are limited by the conditions outlined previously. These problems not withstanding tuning fork oscillators can be built with a stability more than adequate for a large number of applications.

A tuning fork oscillator temperature controlled in a hermetically sealed package may be had with a long term stability of 1 to 1.5 parts in a million. A short term stability of 1 part in 5 million is feasible.

Production items with an accuracy of 100 parts in a million, including all effects of environmental conditions, are standard today. This includes temperature effect, shock and vibration, aging and variation in circuit parameters.

Investigation of various metals for use as resonators, mounting methods, different fork configuration, coupling devices other than electromagnetic, and changes in both circuit configuration and components will in the opinion of the authors allow reduction in size of at least one-third and also obtain a greater resistance to shock and vibration. An improvement in stability, both long and short term, is of the utmost importance. Analysis and study of various modes and configuration need to be made.

Investigation of the use of overtones, "Clang tones", and their stabilities will allow for higher frequencies without the disadvantages inherent in a high frequency fork (13,000 cycles and up). Utilization of these will require design of different mounting and driving configurations.

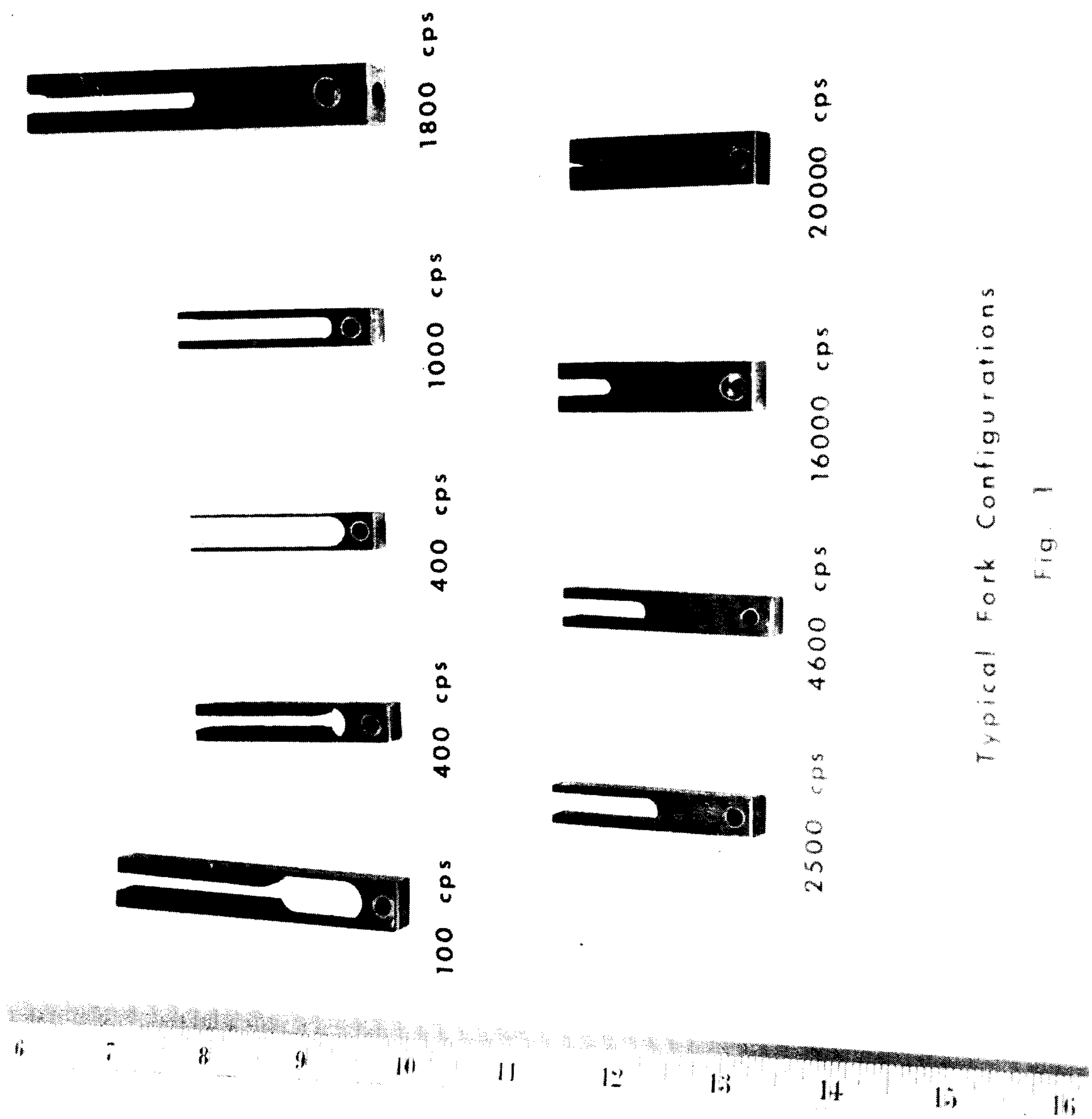
In short, it is felt that the potential for both tuning fork oscillator performance and application is just beginning.

REFERENCES

(1) Koenig - Wiedmann Ann. 1880

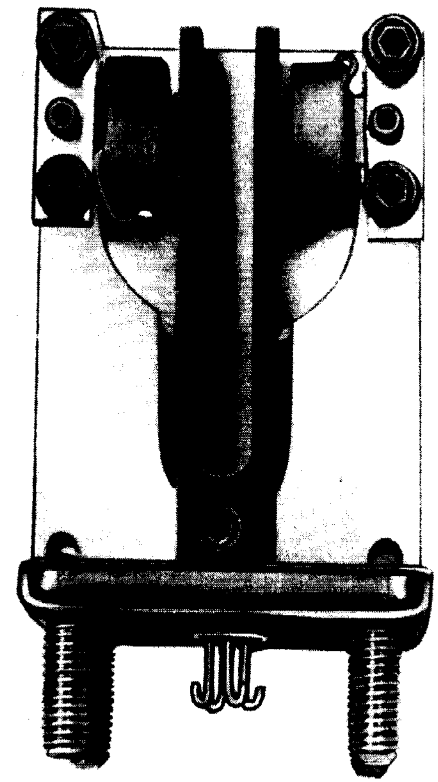
(2) Guilliame - Review de Metalurgie, #25, 1928

(3) Eisenhour - Patent #1,880,923



Typical Fork Configurations

Fig. 1



Typical Fork Assembly

Fig. 2

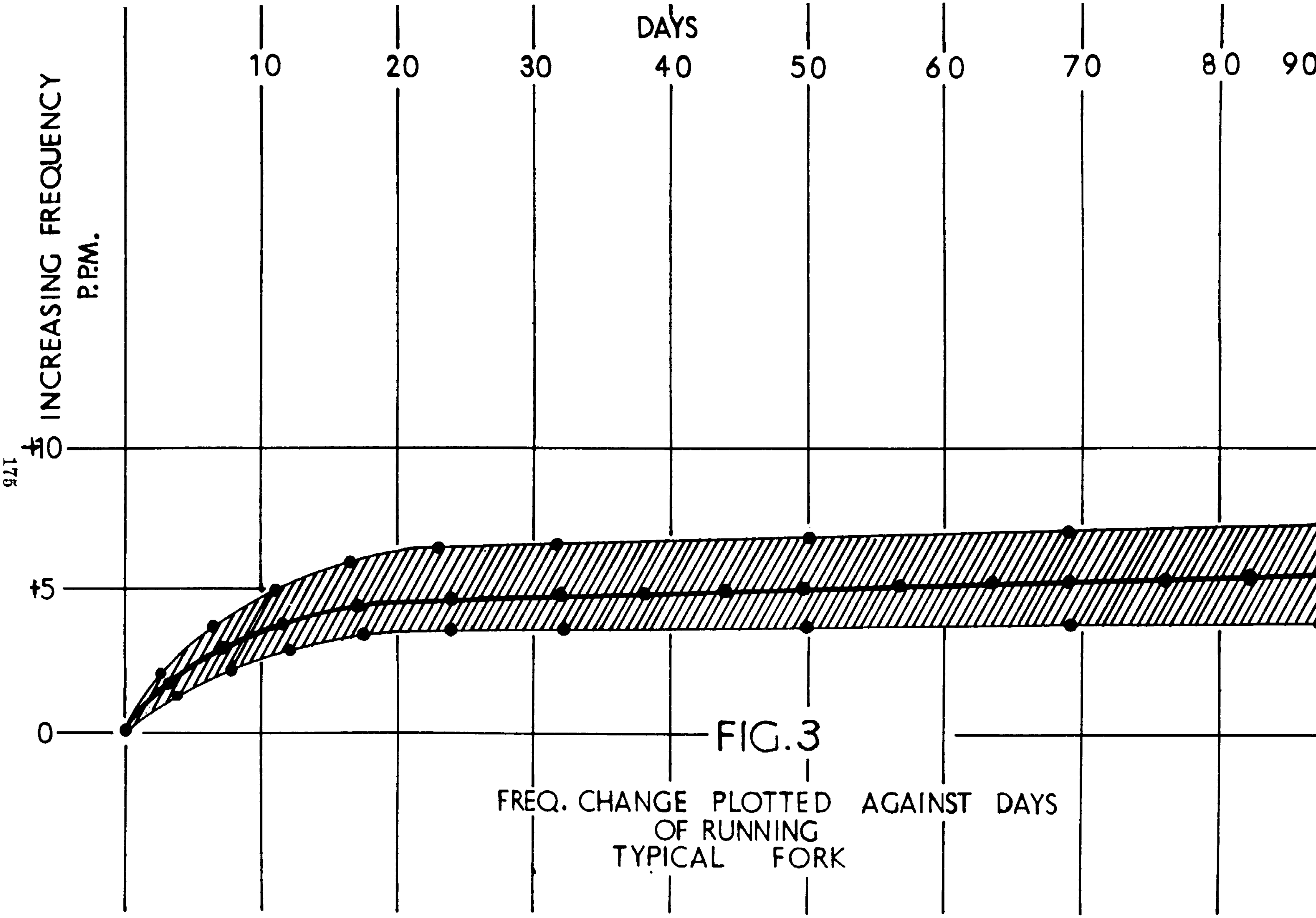


FIG. 3

FREQ. CHANGE PLOTTED AGAINST DAYS OF RUNNING TYPICAL FORK

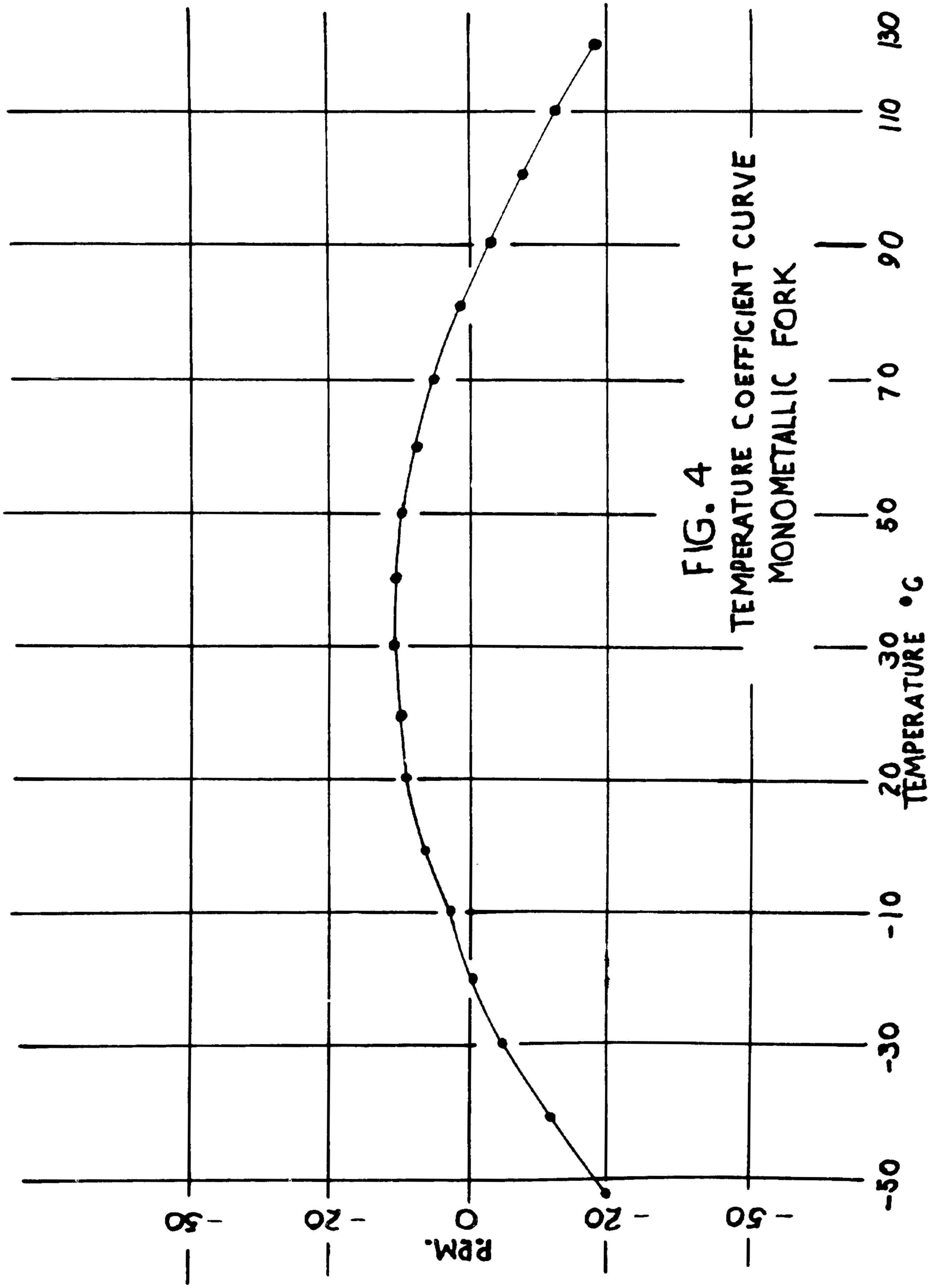
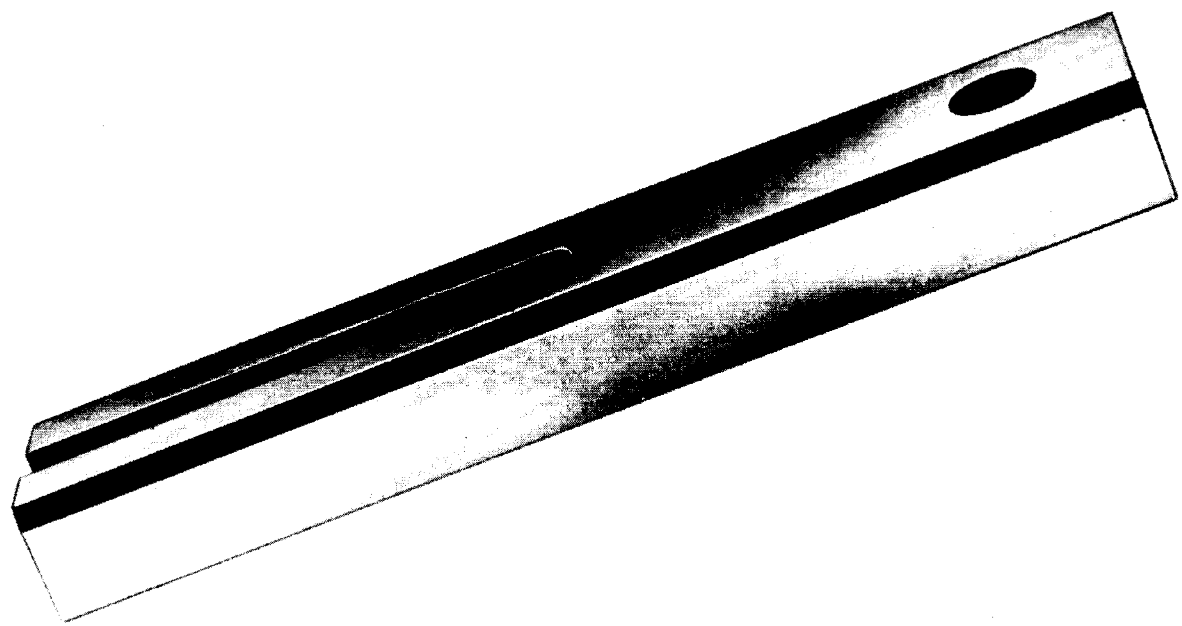


FIG. 4
TEMPERATURE COEFFICIENT CURVE
MONOMETALLIC FORK



Bi-metallic Fork Construction
Fig. 5

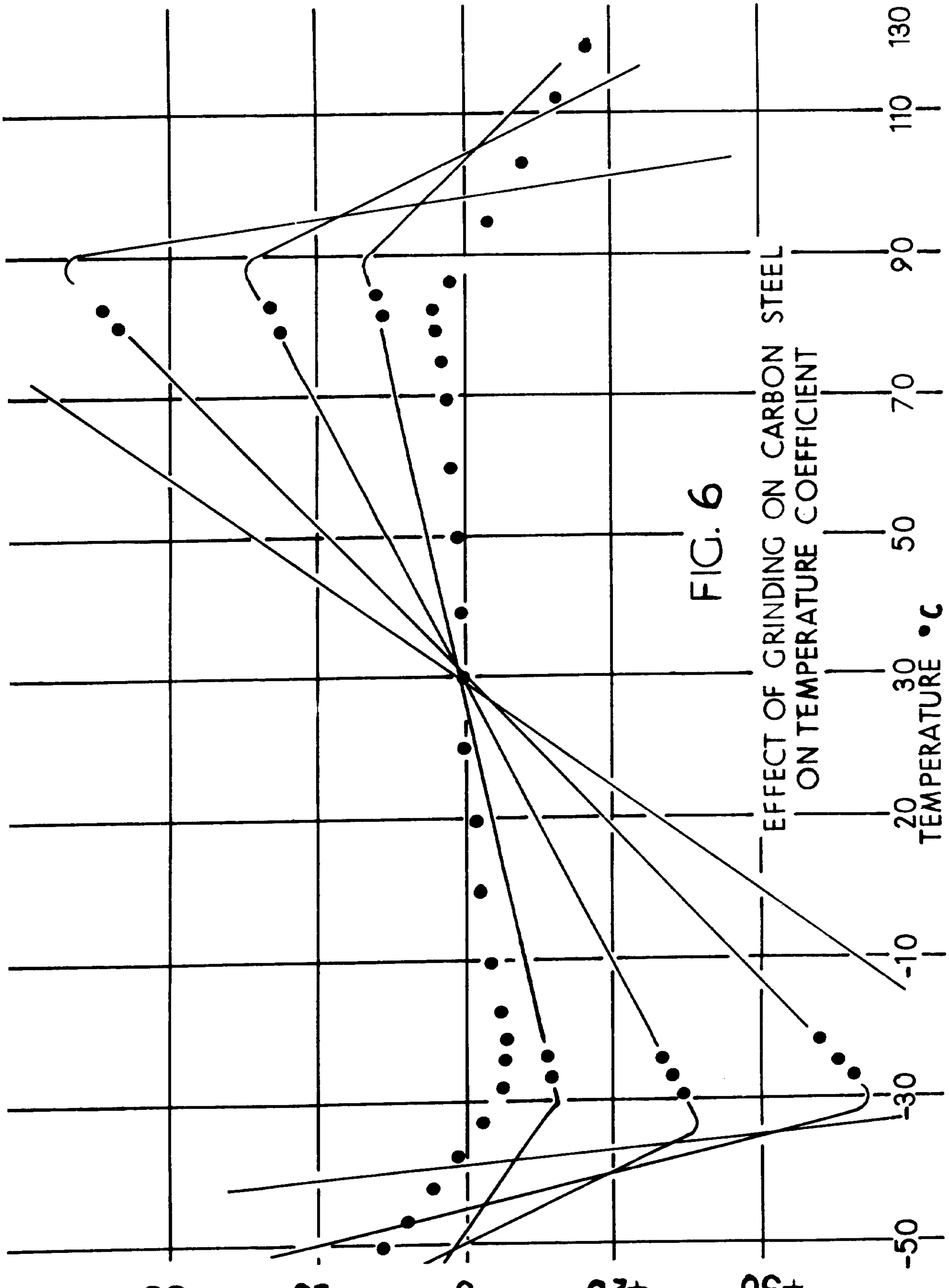


FIG. 6
EFFECT OF GRINDING ON CARBON STEEL ON TEMPERATURE COEFFICIENT

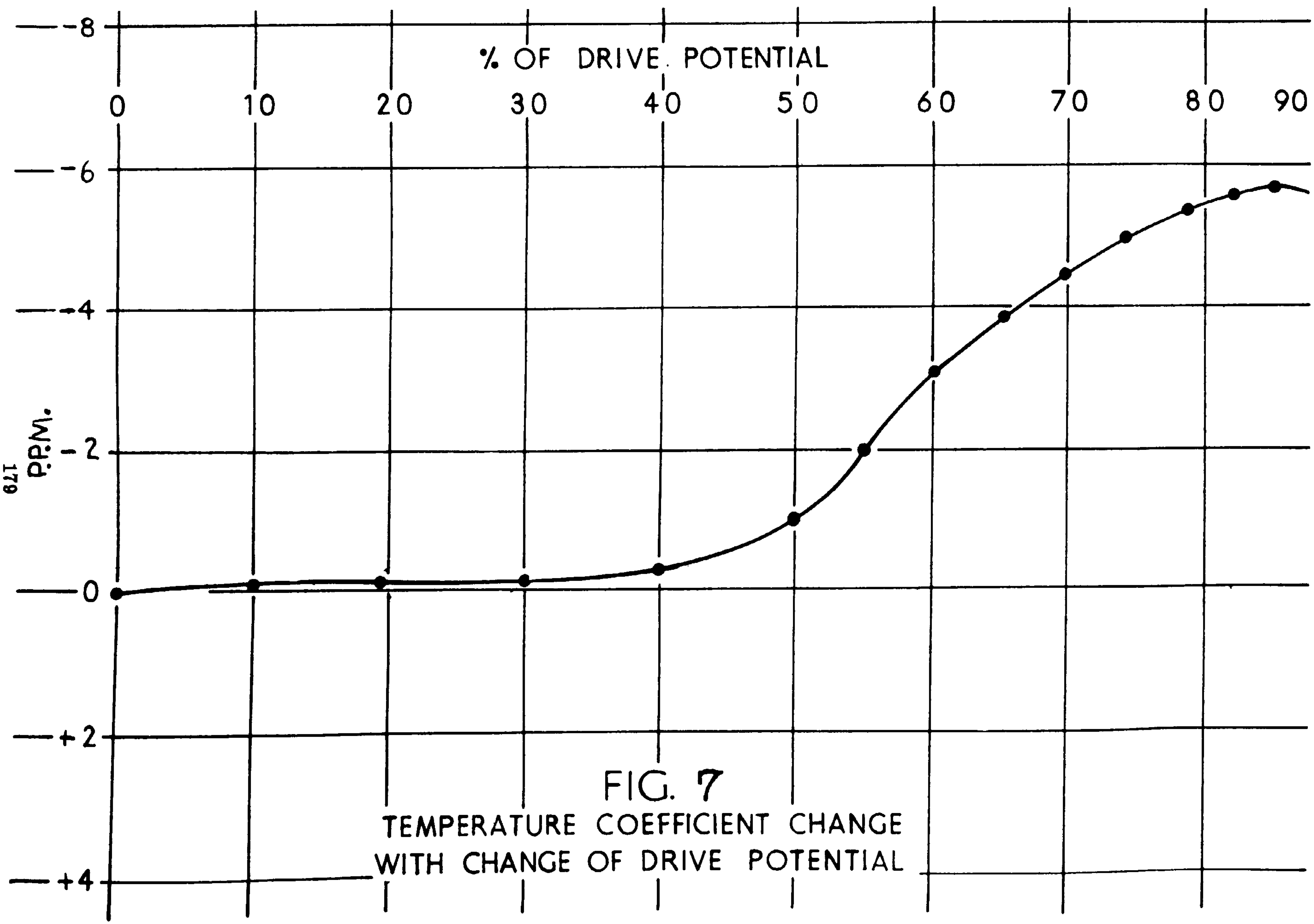
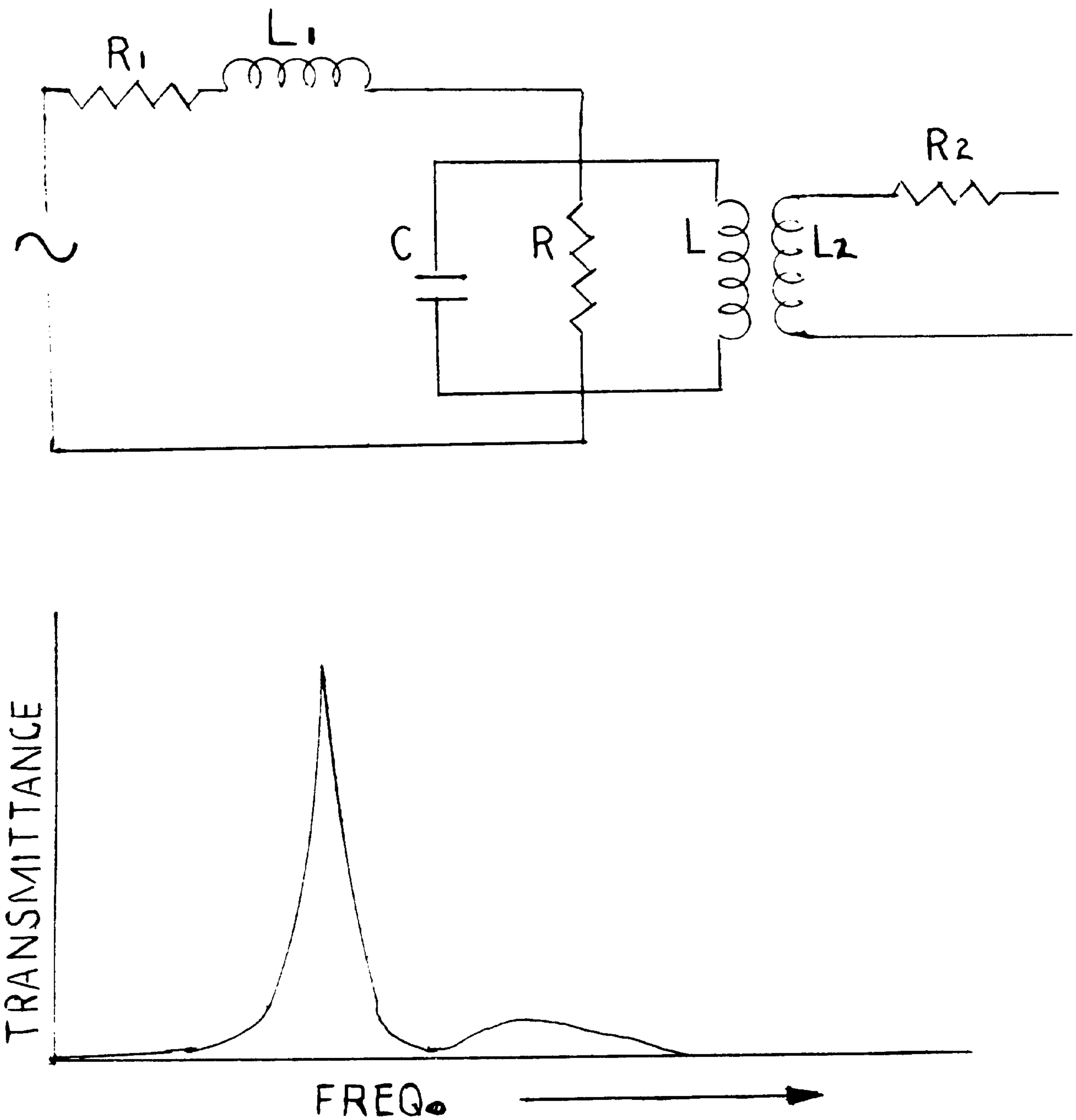
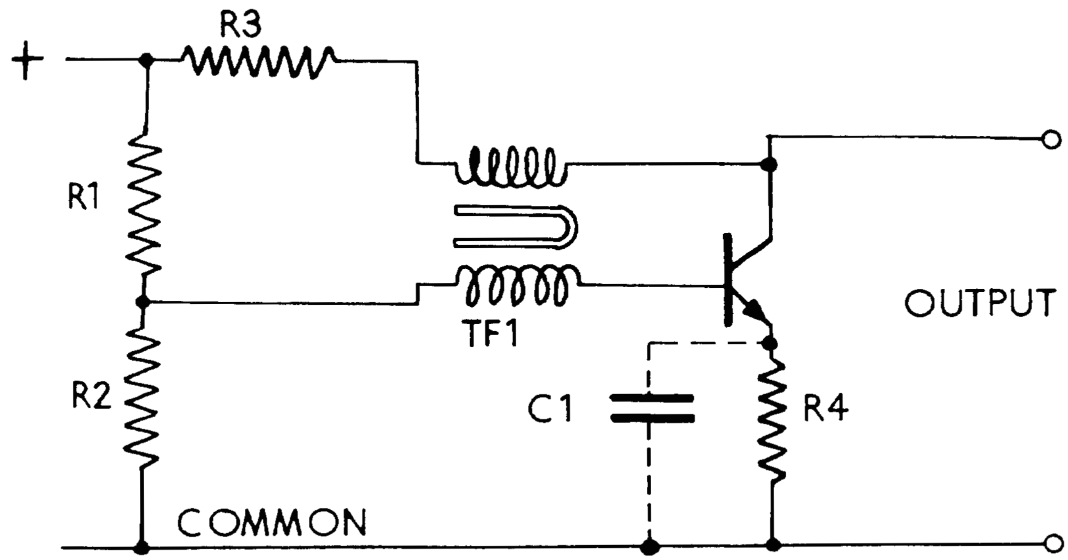


FIG. 7
TEMPERATURE COEFFICIENT CHANGE
WITH CHANGE OF DRIVE POTENTIAL



SIMPLIFIED EQUIVALENT CIRCUIT
FIG. 8



TRANSISTOR TUNING FORK OSCILLATOR

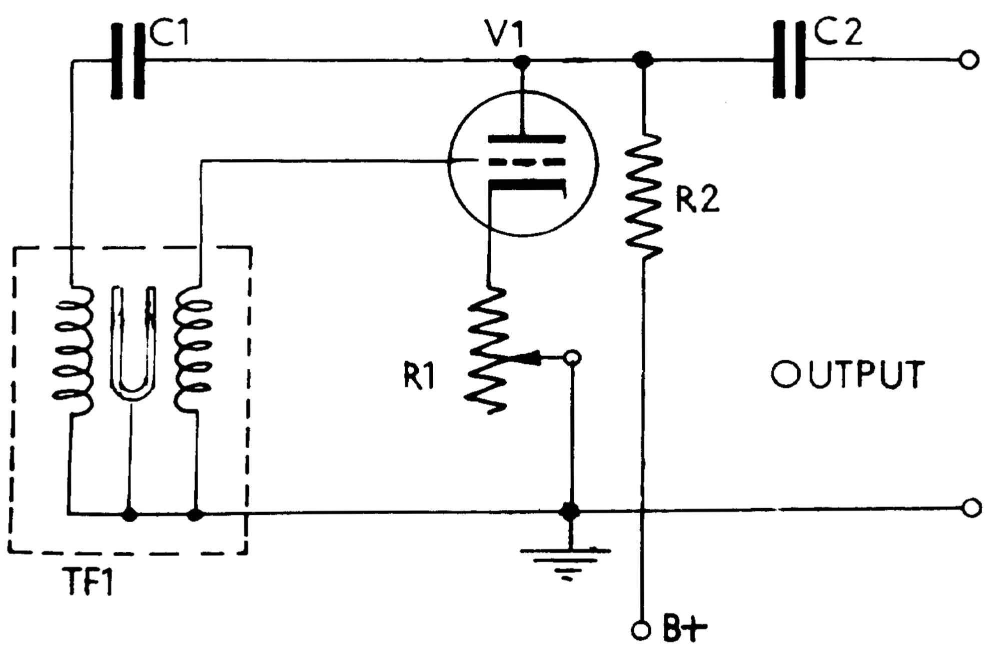


FIG. 9

VACUUM TUBE FORK OSCILLATOR