Oct. 14, 1930.

H. C. HARRISON

1,778,386

SOUND REPRODUCER

Filed June 30, 1928

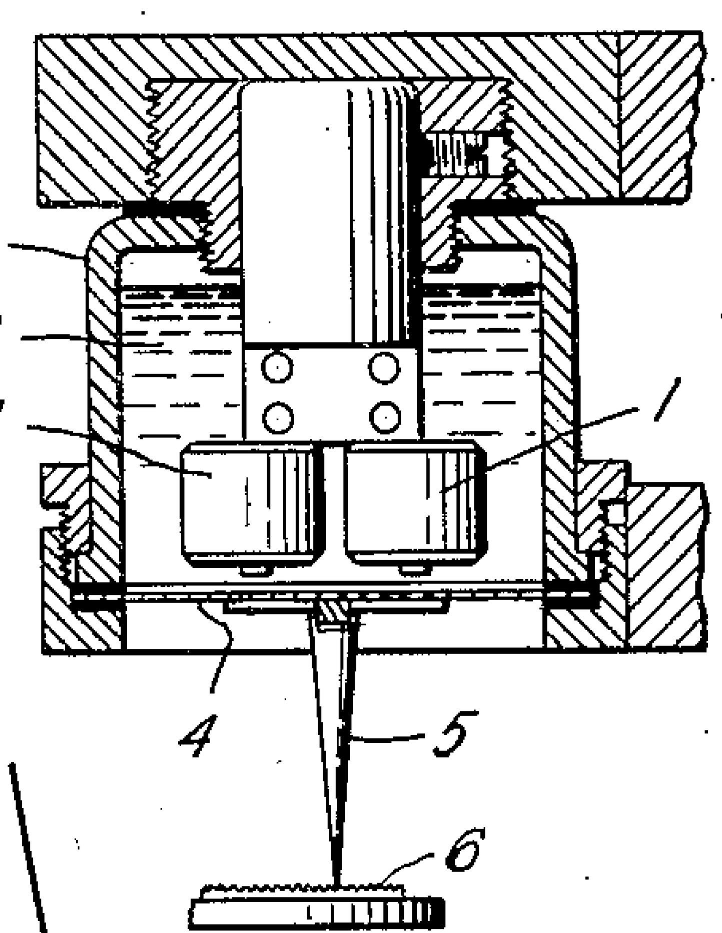

FIG. 1

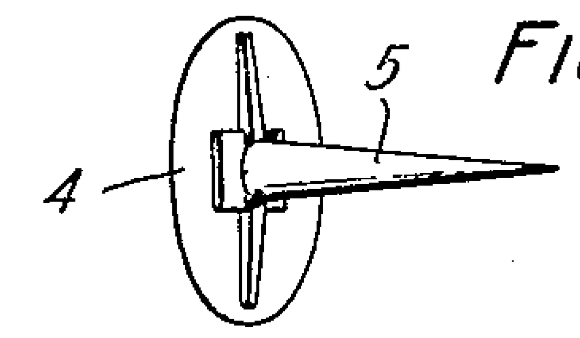

FIG. 2

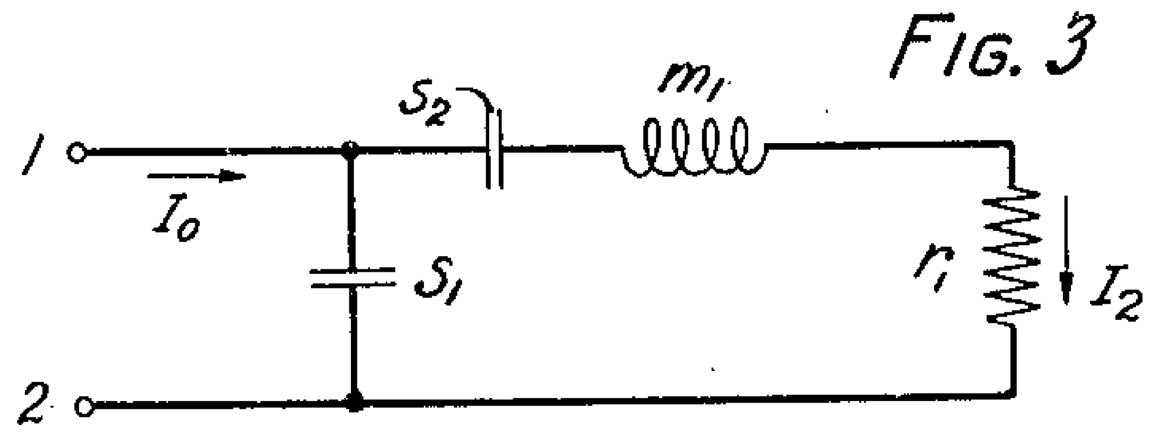

FIG. 3

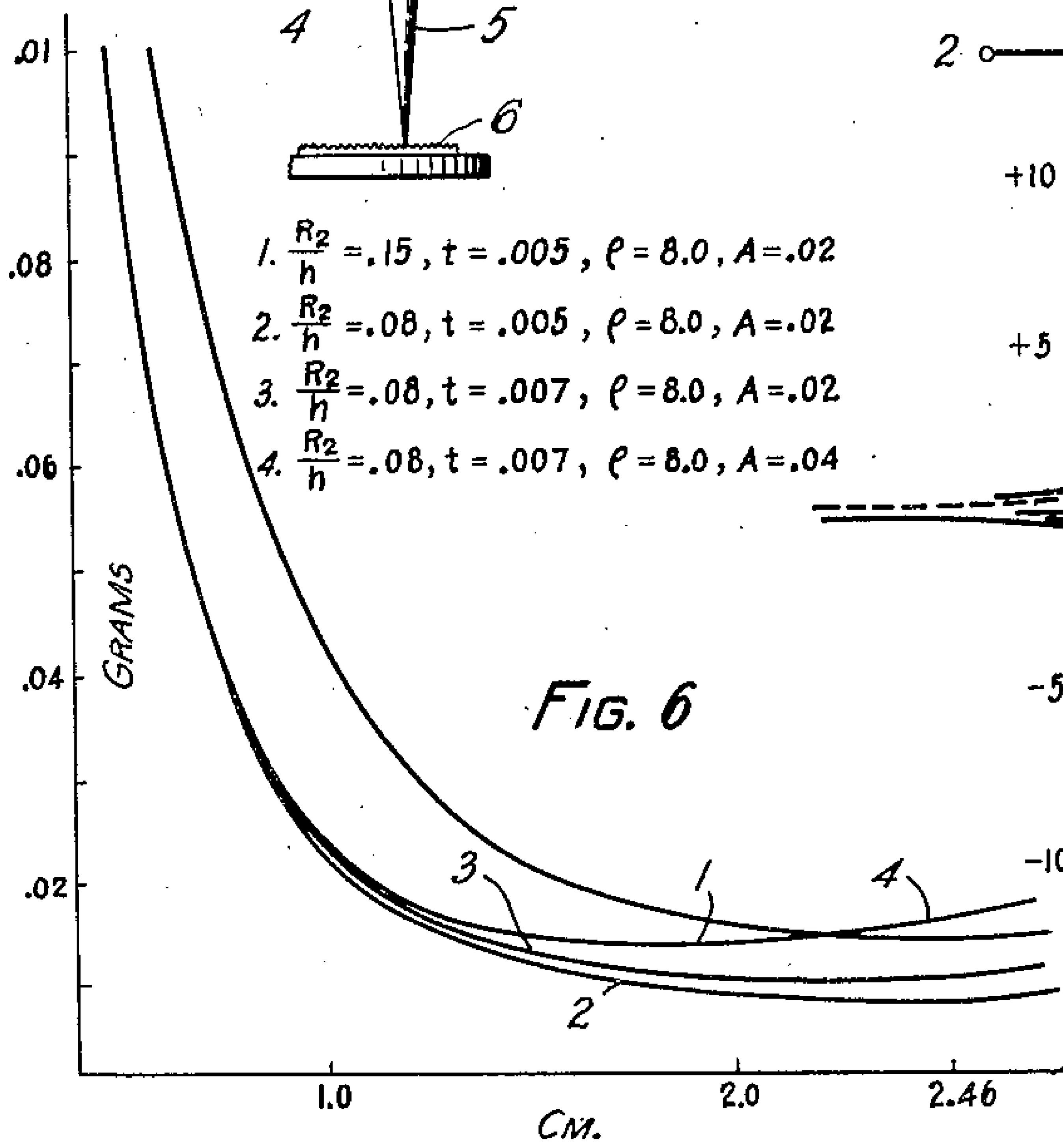

FIG. 6

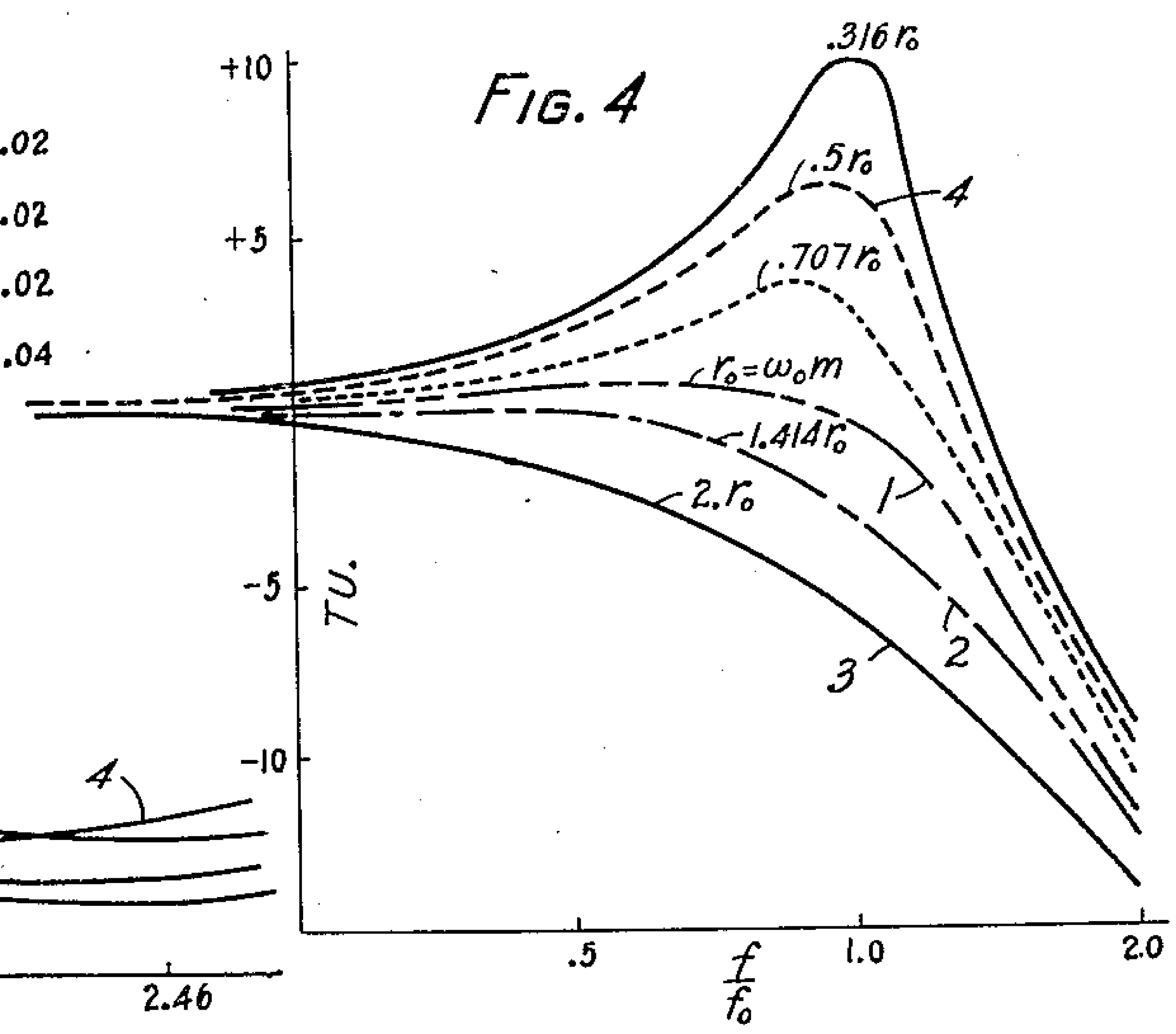

FIG. 4

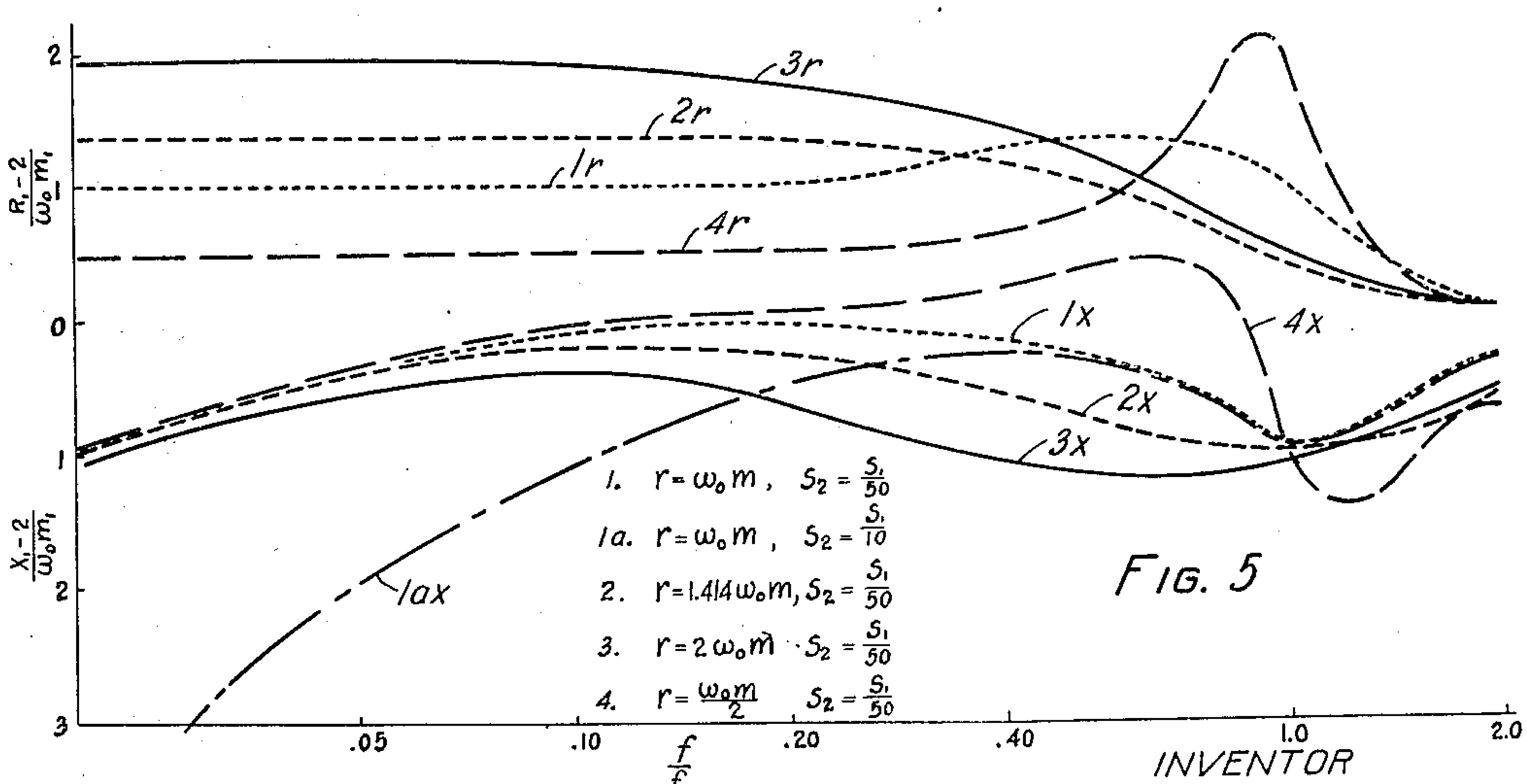

FIG. 5

INVENTOR
HENRY C. HARRISON
BY G. M. Campbell
ATTORNEY

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HENRY C. HARRISON, OF PORT WASHINGTON, NEW YORK, ASSIGNOR TO BELL TELEPHONE LABORATORIES, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK

SOUND REPRODUCER

Application filed June 30, 1928. Serial No. 289,544.

This invention relates to sound reproducing mechanisms and its object is to provide a moving system for reproducers which will respond faithfully to applied forces at the needle point which are of such small magnitude that they will not disrupt or tear the soft wax material in which the original of a production is recorded.

A moving system sufficiently low in mechanical impedance to fulfill the objects of this invention results from the use of a very light, stiff needle which may be connected directly to the translating element of the system and may be made sufficiently long that its mass is the controlling factor in reducing the needle point mass to its lowest value.

A hollow conical needle, the active point of which is an integral part of the cone, has been found quite suitable for the practice of this invention although other forms will readily suggest themselves.

In the drawing Fig. 1 is a sectional assembly view of the reproducer embodying this invention. Fig. 2 is a perspective view of one form of the moving system for a play-back reproducer. Fig. 3 is a representation of the analogs of the mechanical elements of this reproducer in the elements of a corresponding electrical network. Fig. 4 shows a computed frequency response of a mechanical system such as that of Fig. 3. Fig. 5 gives the impedance-frequency curves for various systems with the constants indicated; and Fig. 6 gives the effective values of mass for needles of various lengths.

The stationary structure of this reproducer may be of the general type described in my copending application, Serial No. 191,012, filed May 13, 1927, and consists of electromagnets 1, 1 in a casing 2 containing viscous matter 3. The diaphragm 4 is arranged to be flexed about a diameter by the reaction of the grooves of the record 6 on the needle 5 in the same manner as described in that application except that in the present invention the needle is directly attached to the diaphragm making the usual stylus holder unnecessary.

In order that a play-back reproducer may be capable of faithful response over the whole range of interest, it is necessary not only that the moving system have a very low mechanical impedance but also that the overall response of the reproducer be substantially uniform and reasonably efficient for the various frequencies. In the present invention the above requirements are met by a combination of the following distinct features: (1) a new order of magnitude of the ratio of needle-point stiffness to total mass moving with the needle; (2) the proper value of mechanical resistance or damping; (3) a moving system having no natural periods of vibration within the frequency range to which the reproducer is required to respond; and (4) low balance stiffness of the moving system.

A clearer understanding of the considerations involved in the design of this device may be obtained by considering the mechanical elements as analogs of the corresponding electrical system as set forth in Fig. 3 of the drawing. In this figure the shunt stiffness S_1 represents the needle elasticity of the reproducer; the series stiffness S_2 represents the "balance" elasticity of the system or the difference between the stiffness of the diaphragm and the negative stiffness due to the magnetic effect of the polorizing field m_1 represents the effective mass of the moving system at the needle point; and r_1 represents some means of mechanical dissipation, such as oil damping, introduced into the system.

The impedance Z_{1-2} across the input terminals of the structure of Fig. 3, may be determined for any frequency when constants of the mechanical system from the equation:

$$Z_{1-2}=R_{1-2}+JX_{1-2}'$$

where $R_{1-2}=\omega_0 m_1 \dfrac{\dfrac{r_1}{\omega_0 m_1}}{\left(\dfrac{\omega}{\omega_0}\right)^4-\left[2(1-K_1)-\left(\dfrac{r_1}{\omega_0 m_1}\right)^2\right]\left(\dfrac{\omega}{\omega_0}\right)^2+[1+K_1]^2}$

and $jX_{1--2}=-j\omega_0 m_1\left(\dfrac{\omega}{\omega_0}\right)\left[\dfrac{\left(\dfrac{\omega}{\omega_0}\right)^2-(1+K_1)K_1\left(\dfrac{\omega_0}{\omega}\right)^2\left(\dfrac{r_1}{\omega_0 m_1}\right)^2(1+2K_1)}{\left(\dfrac{\omega}{\omega_0}\right)^4-\left[2(1-K_1)-\left(\dfrac{r_1}{\omega_0 m_1}\right)^2\right]\left(\dfrac{\omega}{\omega_0}\right)^2+[1+K_1]}\right]$

With a view to simplifying the solution of this equation curves showing values of the ratios $\dfrac{R_{1-2}}{\omega_0 m_1}$ and $\dfrac{X_{1-2}}{\omega_0 m_1}$ plotted against the ratio $\dfrac{f}{_0f}$ have been given in Fig. 5 for different values of mechanical resistance r_1. From curve $1r$ of the figure, it is evident that the conditions for smoothness of frequency response also lead to a smoothness in the impedance characteristic if the series stiffness S_2 is small as it is in this case. If the series stiffness is made larger, keeping the resistance at $\omega_0 m$ as before, the impedance response is very materially affected, particularly at low frequencies as indicated by the curve $1a$. These two curves show the importance of low effective balance elasticity if the mechanical impedance at low frequencies is not to become excessive. It is evident then that by the proper choice of mechanical resistance and series stiffness a reproducer of approximately constant impedance at all frequencies up to resonant frequency can be made.

The importance of the first of the above considerations is due to the fact that the natural frequency of the system is directly proportional to the square root of this ratio as shown by the equation $f_0=\dfrac{1}{2\pi}\sqrt{\dfrac{S_1}{m_1}}$. Since the mechanical impedance of a system in parallel resonance is very high, the response of the system will fall off very appreciably as this natural frequency is approached. It is evident then that for a high quality reproducer the natural frequency should be as high as possible. In this reproducer this ratio, $\dfrac{S_1}{m_1}$ has been made very high by reducing the mass of the moving system to the lowest practical value and by employing a needle of unusual stiffness so that the natural frequency of the system is in the neighborhood of the upper limit of the frequency range to be reproduced.

With respect to the second of these features, care must be taken in adjusting the value of the terminating impedance r_1 so that the impedance of the system at terminals 1 and 2, corresponding to the needle point, will be substantially uniform for all the frequencies involved. The natural periods of the component parts of the moving system, such as the diaphragm and the needle, must be made very high to prevent the introduction of high shunt impedances which would make it impossible to obtain a uniform characteristic over the whole range.

The balance stiffness of the moving system, as represented by S_2 in the drawing, must be made very low to prevent high impedance at low frequencies. While the actual value of the balance stiffness cannot be reduced below a certain value without causing instability, the effective stiffness is made very small due to the unusual length of needle employed.

In the design of this reproducer the computed frequency response for the structure for constant input velocity is given by the following equation:

$$\text{Loss in } TU=10\log\left(\frac{I_0}{I_2}\right)^2=10\log\left[\left(\frac{\omega}{\omega_0}\right)^4+\left(\frac{\omega}{\omega_0}\right)^2\left[\frac{r_1^2}{\omega_0^2 m_1^2}-2(1+K_1)\right]+(1+K_1)^2\right]$$

where I_0=input velocity to the network shown in Fig. 3 in cms. per second; I_2=the output velocity from the network cms. per second; m_1 is the effective mass; S_1 the shunt elasticity; S_2 the series balance elasticity and r_1 the mechanical resistance all effective at the needle point; $\omega=2\pi f$, f being the frequency considered; $\omega_0=2\pi f_0$; $f_0=\dfrac{1}{2\pi}\sqrt{\dfrac{S_1}{m_1}}$ being the needle free resonant frequency; and $K_1=\dfrac{S_2}{S_1}$. Since $\dfrac{\omega}{\omega_0}$ is equal to $\dfrac{f}{f_0}$ it follows that the above equation gives the relative response of the system for a frequency range which is independent of the absolute efficiency of the structure under consideration.

The needle free resonant frequency having been determined by the equation $f_0=\dfrac{1}{2\pi}\sqrt{\dfrac{S_1}{m_1}}$, the relative response at various frequencies may be modified by varying the mechanical resistance r_1. For the purpose of determining the proper value of mechanical resistance, it has been found convenient to plot curves, such as those shown in Fig. 4, which show the response obtained with various effective values of r_1 expressed in terms of the resistance at resonant frequency. It is evident from these curves that best results are obtained when $r_1=\omega_0 m_1$; in this case the variation up to resonant frequency is less than 1 TU; but in cases where smaller values of r_1 are used a peak appears in the response curve near resonant frequency, while for other values greater than $\omega_0 m_1$ the response drops off faster than for the ideal value.

In the design of the needle, advantage was taken of the higher ratio of stiffness to effective mass of hollow sections of thin wall material over solid material. The moment of inertia for a hollow conical needle of thin wall material taken about the diameter of its base is given by

$$I=\frac{\pi}{15}R_2\rho h\,t\,(2R_2^2+h^2)$$

where R_2 is inside radius of the base; h is the length of needle; t is the thickness of the wall and ρ is the density of material. If to this we add the necessary moment of inertia of the armature denoted by A, we have then for the effective mass at the needle point:

$$m_1=\frac{I+A}{h^2}=\frac{\pi}{15}\left(\frac{R_2}{h}\right)\rho t\left[h^2x2\left(\frac{R_2}{h}\right)^2+1\right]+\frac{A}{h^2}$$

For constant needle stiffness with variation in length h, it is necessary to maintain the ratio $\frac{R_2}{h}$ constant. If we differentiate the above expression with respect to h for m_1 minimum, we find that

$$h^4=\frac{15A}{\pi\left(\frac{R_2}{h}\right)\rho t\left[1+2\left(\frac{R_2}{h}\right)^2\right]}$$

This equation shows that h will not vary greatly for a rather wide range of values of A, t or $\frac{R_2}{h}$, but gives no indication as to the variation of m_1 for values of h other than the minimum value. The curve of Fig. 6 is therefore given to show the value of m_1 for wide range of values of h and various values of A, $\frac{R_2}{h}$ and t.

With the bi-polar reproducer structure which has been found satisfactory for this device, the moment of inertia of the armature together with that of the effective diaphragm mass is approximately .04 gm. cms.^{2}. If $\frac{R_2}{h}$ is equal to .08, $t=.004$ cms. $\rho=8.0$. We find for a minimum mass m_1 (1.010 gms.) that $h=2.46$ cms. It is then necessary to determine if a needle with these constants is stiff enough to give a sufficiently high needle free resonant frequency for good quality reproduction. The stiffness of a hollow conical needle which has a wall thickness very much less than the radius of the base is given very approximately by the formula:

$$S=\frac{\pi E R_2^3 t}{h^3}$$

where E is Young's modulus and the other symbols are of the same significance as before. For the values assumed above, we find that the needle stiffness is equal to

$$\pi\times 2.0\times 10^{12}\times 512\times 10^{-6}\times .004=$$
$$12.8\times 10^6 \text{dynes/Cm.}$$

Corresponding to this, we find the resonant frequency to be:

$$f_0=\frac{1}{2\pi}\sqrt{\frac{12.8\times 10^6}{.010}}=5700 \text{ cycles.}$$

This frequency being near the upper limit of the frequency range recorded, such a reproducer will cover the whole range at substantially constant efficiency.

As already stated, it is found that the impedance is more nearly constant over the whole frequency range when r_1 is made equal to $\omega_0 m_1$. If then we have for this reproducer $\omega_0=2\pi\times 5700$, and $m_1=.010$, then r_1 is equal to 360 mechanical (c. g. s.) ohms effective at the needle point distance of 2.46 cms. This has been found to require a resistance in the gap between the diaphragm and pole pieces of approximately 10,000 mechanical ohms, which can be obtained by using a gap of these dimensions $l=\frac{3}{8}''$, width $b=\frac{1}{4}''$ and the distance between the damping surface $d=.009''$ approximately.

These dimensions of l and b correspond to the dimensions used in the bi-polar armature of my application previously referred to, so that when using a structure of this type, it is only necessary to set the air gap at approximately .009''. If this condition, which corresponds to $r_1=\omega_0 m_1$, is obtained and S_2, the series stiffness, is made less than $\frac{S_1}{50}$, or in this case to a value less than $.25\times 10^6$ dynes, then for any frequency above about 100 cycles or .02 $\frac{f}{f_0}$ in Fig. 5, we shall have for the maximum value of impedance Z_{1-2} maximum=

$$\sqrt{R^2_{1-2\,\max.}+X^2_{1-2\,\max.}}$$

Taking the maximum of R_{1-2} and X_{1-2} from curves $1r$ and $1x$ we get Z_{1-2} maximum=

$$\sqrt{1.34^2+1^2}=1.67\omega_0 m_1.$$

In the case considered. at 50 cycles the impedance will be approximately 2.25 $\omega_0 m_1$ or 800 mechanical ohms. A reproducer of these characteristics has been found sufficiently low in impedance to follow the groove of a soft wax record without damaging it for its further use in the production of permanent records.

In a high quality device of this sort the efficiency must be sacrificed to obtain the necessary smoothness of response but it is of course desirable that the efficiency shall be as high as is consistent with the quality desired. By actual test reproducers designed in accordance with the description given have been found to have an efficiency in excess of $\frac{1}{10}$ of one per cent.

What is claimed is:

1. In a sound reproducing mechanism, means for producing mechanical vibrations, a vibration translating device, and a stylus needle pivoted directly on the translating device and cooperating with the mechanical vibrational means.

2. In a sound reproducing mechanism, a grooved record surface, a vibration translating device, and a stiff light needle pivoted directly on the translating device and cooperating with the record surface.

3. In a sound reproducing mechanism, a grooved record surface, a vibration translating device, and a hollow conical needle connected directly with the vibration translating device and engaging the grooved record surface.

4. A moving system for sound reproducing devices in which the effective values of the mass and stiffness are reduced to a minimum by means of a long light needle connected directly to the vibration translating device.

5. A moving system for sound reproducing devices in which the ratio of needlepoint stiffness in dynes per centimeter to the total effective mass in grams of said system is of the order of 10^9.

6. A moving system for sound reproducing devices including a needle with an unsupported length in excess of ½″, the system having its mass and stiffness so proportioned that its lowest resonant frequency is higher than 5000 cycles.

7. In a sound reproducer, a magnetic circuit carrying a polarizing flux and having a stationary portion and a moving portion, an elastic mounting and damping means for the moving portion and a stylus connected to the moving portion, the polarizing flux, the stiffness of the mounting and the length of the needle being so proportioned that the effective series stiffness of the moving system is reduced to the minimum value consistent with stable operation.

8. In a sound reproducer, a moving system comprising a stylus, an armature and mounting means therefor, having its mass and its elasticities expressed in c. g. s. units so proportioned that its lowest resonant frequency f_0 is higher than 5000 cycles and means for damping the system so adjusted that the damping effective at the stylus point is substantially equal to $2\Pi f_0 m$ mechanical ohms.

In witness whereof I hereunto subscribe my name this 29th day of June, 1928.

HENRY C. HARRISON.