RECTILINEAR FLUID FLOW GENERATOR
OF OSCILLATING TYPE

by

W. H. Hoppmann II

and

E. Kiss

Office of Naval Research

Contract No. Nonr-591(20)

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ABSTRACT

A rectilinear fluid flow generator of an oscillating type has been developed for the purpose of studying the rheological properties and flow characteristics of both Newtonian and non-Newtonian liquids [1][1]. It consists essentially of a long horizontally supported straight tube which can be filled with a liquid in which an equally long concentric cylinder can be oscillated axially in harmonic motion at a predetermined frequency and amplitude. The external tube is mounted on elastic supports of measurable stiffness so that its natural frequency of axial oscillation can be readily calculated. Also, the motion of the external tube and the resultant force acting on it are readily measurable at any time. The principle of the apparatus depends on the fact that the outside tube is moved only by the liquid which itself is caused to flow by the controlled oscillations of the inside tube. It is assumed, at least in principle, that if the motion of the outside tube is known for a given motion of the inside cylinder, the constitutive equations for the liquid can be determined. Or conversely, if the constitutive equations are known, the motion of the outside tube can be calculated for a given motion of the driving inside cylinder.

It has been shown that for infinitely long concentric tubes, of which the inner is constrained to oscillate harmonically and the outer is spring supported, the equations of motion for a Newtonian liquid in the annulus between the tubes can be solved [2]. It turns out that

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[1] Numbers in brackets refer to references at end of report.

the solution is important for the study of the motions of the apparatus now under consideration. The application of the solution is demonstrated in this report.

The purpose of the apparatus which has been developed is two-fold:

(a) to determine rheological properties of given liquids, such as the coefficient of viscosity for Newtonian liquids;

(b) to observe various flow phenomena, especially the action of drag reducing solutions of high polymers.

Since the external tube is made of glass, microscopes and flow visualization techniques can be used to study the nature of the flow.

INTRODUCTION

Various kinds of viscometers [3] and rheogoniometers [4,5] are used to determine the rheologic properties of liquids. These devices range from very simple capillary tube arrangements to fairly complicated machines. It is considered that as useful as these devices may be to answer some questions about resistance to flow in liquids, there is yet no satisfactory means available for the complete determination of constitutive equations. The solution of this vexatious problem does not seem to be in sight. Accordingly, rheologists will continue to search for more universally applicable devices in order to increase knowledge of constitutive equations. There probably is no single machine which will provide all of the information required.

The determination of constitutive equations depends essentially on the solution of the equations of motion for any liquid under study. Of course, the simpler the design of the apparatus the greater the probability, in general, of solving the equations of motion for the liquid flowing in that apparatus. The purpose of the present report is to introduce an experimental apparatus of relatively simple design for the study of the properties of liquids. It is considered that for Newtonian liquids the equations of motion have been solved at least with an acceptable degree of approximation. The apparatus is considered to be novel and lends itself to the study of important aspects of flow.

DESCRIPTION OF THE APPARATUS

The flow generator, shown in Fig. 1, consists essentially of an outer glass tube supported by flat steel springs and an inner aluminum tube fitted on its ends to hardened steel shafts which rest in bearings. The inner tube is driven by means of an eccentric to which a crank and guided rod are attached. A fractional horsepower motor with a thyratron speed control is used to supply the power to operate the device. The speed control can be set to provide the predetermined operating frequency of the oscillating inner tube. The eccentric can be readily set to provide the amplitude of rectilinear motion desired. Reservoirs of flexible rubber or other liquid impervious materials are located at each end of the generator to permit the free movement of the external tube but yet hold the liquid under study properly in place.

The inner tube is supported in lineal bearings which are fixed to the rigid base of the apparatus. The outer tube is supported by flat steel springs which are attached securely at their tops to a flat bar and at their bottoms to aluminum rings which are securely clamped to the glass tube itself. The upper bar is bolted at each end to fixed vertical supports.

An important dimension of the apparatus is the thickness h of the annulus. In order to increase the force acting in the outer tube for a given motion of the inner tube, h should be kept as small as possible. Two factors militate against this condition, the tolerance of the manufactured tubes and the degree of alignment of tubes which is mechanically possible. For the present study, the diameter of the inner tube was 0.875 inch and the inner diameter of the glass outer tube was 1.000 inch. The annulus thickness was therefore 0.125 inch. The clearance and alignments were kept within ± 0.010 inch. The thickness of the glass tube was approximately 0.25 inch.

The length of the outer tube was approximately five feet. It had tapered fittings of aluminum attached to the ends so that the portion moving in the liquid in the reserviors would develop as little resistance as possible[2]. The tapers ended in feathered edges about 0.005 inch thick and rounded. The inner tube with its metal extension through the end bearings was, of course, longer.

For various purposes it may be desirable to change the natural frequency of the outer tube system. Accordingly, arrangements were provided to add mass to the surface of the tube by clamping on pieces of iron and to alter the stiffness by changing the size of the flat steel spring supports.

Strain gages attached to the steel spring supports enable one to measure the spring force acting on the glass outer tube. Standard strain measuring and recording equipment was used. The total shearing force at the interface of the liquid under test and the inside surface of the outer tube can readily be calculated from a knowledge of the spring force and the inertia force acting on the tube. The inertia force is readily calculable from the known harmonic motion of the tube.

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[2] These do not show on sketch in Fig. 1.

The characteristic motion of the system may be compared with that obtained from the solution of the Navier-Stokes equations for infinitely long concentric tubes having the outer tube supported elastically and the inner tube driven harmonically with a specified frequency and amplitude [2].

THEORY OF THE OSCILLATING FLOW OF NEWTONIAN LIQUID

It is important to have a solution of the equations of motion for the liquid in an apparatus of the type under discussion, at least for a Newtonian liquid. As is well-known very few problems on viscous laminar flow have been solved and the present case is not one of them. It does turn out, however, that the Navier-Stokes equations can be solved for infinitely long tubes, of which the external one is elastically supported along its length and the concentric inner tube is harmonically moving in steady motion [2]. It is also assumed that the flow is isothermal, steady-state and incompressible. In this case, the flow in the annulus will be rotationally symmetric, and will also be independent of z. A schematic drawing of a section of such tubes is shown in Fig. 2.

The radial and tangential velocity components u and v will vanish. The third velocity component w, which is the axial or longitudinal component, can be shown to satisfy the following equation of motion [2]:

$$\rho \frac{\partial w}{\partial t} = \mu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} \right) \qquad (1)$$

The continuity equation is readily satisfied because u and v vanish and w is assumed to be independent of the coordinate z.

The boundary condition at the inner boundary of the liquid, that is no slip condition, is:

$$w(a,t) = V_0 \cos \omega t \tag{2}$$

where
a = radius of inner tube
V_0 = maximum velocity of inner tube
ω = frequency of oscillation of inner tube
t = time
w = velocity in liquid

If Z is the longitudinal displacement of any point on the outer tube then a section of length L will move according to the following equation of motion

$$\ddot{Z} + p_n^2 Z = \frac{F(t)}{M_0} \tag{3}$$

where
p_n = natural frequency of a length L of tube on elastic foundation
M_0 = mass of the length L of tube
$F(t)$ = shearing force of liquid acting on the tube of length L

The shearing stress on the inner surface of the outer tube is:

$$\tau_{rz} = \mu \left.\frac{\partial w}{\partial r}\right|_{r=b} = \frac{F}{2\pi bL} \qquad (4)$$

where μ = coefficient of viscosity

b = inner radius of outer tube

Then the second boundary condition to be satisfied is

$$w(b,t) = \dot{Z} = \frac{2\pi bL}{M_0}\,\mu \int_0^t \frac{\partial w(b,\tau)}{\partial r} \cos p_n(t-\tau)\,d\tau \qquad (5)$$

The solution $w(r,t)$ is obtainable in terms of the Kelvin functions ber, bei, ker, and kei [2]. A simpler asymptotic solution is obtainable and can be used for

$$kr > 8$$

where $k = \sqrt{\frac{\omega}{\nu}}$

This can also be written

$$\frac{fa^2}{\nu} > 1.6 \qquad (6)$$

where f = natural frequency in c.p.s.

ν = coefficient of kinematic viscosity in Stokes

and a = radius of inner tube in inches.

An important factor for the use of the experimental apparatus is an equation for the drag per unit length on the external tube. It can be written as follows [2]:

$$\left(\frac{F_0}{L}\right)_{\max} = 2\pi b\mu\, V_0\ k\, \xi_0(\alpha) \tag{7}$$

where $\xi_0(\alpha)$ is a dimensionless function computed from the asymptotic solution. It is plotted in Fig. 3 for a range of α, where α is as follows:

$$\alpha = \frac{k}{\sqrt{2}}(b-a) = \frac{kh}{\sqrt{2}} \tag{8}$$

The coefficient of viscosity μ can be calculated from the approximate equation (7). For the apparatus described herein the equation is valid up to a viscosity of about 800 centipoises, which is that for castor oil.

To use the curve for $\xi_0(\alpha)$ the following relations are given:

$$\begin{aligned} \xi_0(\alpha) &= c_1\, \nu^{-\frac{1}{2}} \\ \alpha &= d_1\, \nu^{-\frac{1}{2}} \\ c_1 &= \frac{(F_0/L)_{\max}}{2\pi b\rho\, S_0\omega^{3/2}} \\ d_1 &= \sqrt{\frac{\omega}{2}}\ h \\ m &= \frac{c_1}{d_1} \end{aligned} \tag{9}$$

c_1 and d_1 can be readily calculated in terms of the given quantities. Hence m is then known. The intersection of the m equals a constant line and the $\xi_0(\alpha)$ curve in Fig. 3 gives the required value of ξ_0 and α in order to determine the coefficient of kinematic viscosity ν.

RESULTS AND CONCLUSION

The rectilinear flow generator which has been developed appears to offer promise of becoming a useful tool in the study of flow of both Newtonian and non-Newtonian liquids. It is based on a relatively simple principle and permits ready measurement of stresses and observation of flow lines. The axial or longitudinal motion of the inner cylinder can be readily maintained so that if harmonic motion is desired, the amplitude and frequency can be determined accurately. For Newtonian liquids, the corresponding problem of oscillating flows between infinite co-axial cylinders has been solved [2]. A drag force equation based on the solution has been developed for the present type generator and it is considered to be accurate up to viscosities of about 800 centipoises.

The usual end effects which arise because of the finite length of the cylinder appear to be negligible because of the lack of pressure rise and disturbance in the reservoir of liquid at the ends of the tube. The fact that calculated viscosities for various liquids check within a few percent known viscosities gives some evidence for this conclusion, also. The flow, as examined by dye injection techniques, also seemed very uniform throughout the length of the apparatus, steadily following the motion of the inner tube. Of course, there is a phase difference between the motion of the outer tube and the inner drive tube.

The drag force on the outer elastically supported tube can be easily measured with any desired accuracy. On the assumption of uniform conditions along the entire length of the tube, the shearing stress can therefore be readily determined. Also, the frequency and amplitude of the motion of the inner tube are easily measured.

A peculiar drag-frequency relation predicted by the theory [2] is clearly shown in Fig. 4 and Fig. 5. It is demonstrated that the drag on the outer tube drops to zero when the inner tube is driven at the natural frequency of the outer tube system. If the apparatus is to be used as a viscometer it is better to operate at a frequency well below this value because of the rapidly changing drag as function of frequency at that point. It would be very interesting to see what happens to the drag-frequency curve when non-Newtonian liquids are used.

The theoretical velocity ratio and displacement ratio of the two tubes as functions of frequency are interesting. They are shown in Fig. 6. However, no attempt was made to check them experimentally in the present study.

Some difficulties arise from vibrations in the supporting structure of the generator and various stiffening devices were used to eliminate them. In case the generator is used extensively in flow research it is strongly recommended that the supporting frame be made in the form of a single rigid casting.

The natural frequency of the outer tube system can be readily designed to any value by changing the mass and spring support stiffness. The control of this feature of the apparatus is quite good.

The most satisfactory operating conditions occur when the annulus thickness is small compared to the radius of the inner tube. In that case the forces on the external tube are larger and therefore much more readily measurable. Also, smaller quantities of liquid are required for the experiment. For the experiments performed with the present generator less than 50 cubic inches of liquid were required for each experiment. It is apparent that the narrower the annulus the more difficult is the problem of alignment. However, the dimension used in the present investigation proved satisfactory and it is well within the capabilities of good instrument makers to provide any required precision.

Some of the experiments now planned for the generator require higher operating speeds to investigate the question of stability of flow and possible turbulence. Also, a most interesting question concerns the study of various non-Newtonian liquids such as those investigated with the rotational fluid flow generator [6]. The apparatus is suitable for using micro-photography in studies of flow lines for various kinds of liquids. The action of drag reducing agents can be studied and should provide further knowledge of these important chemicals.

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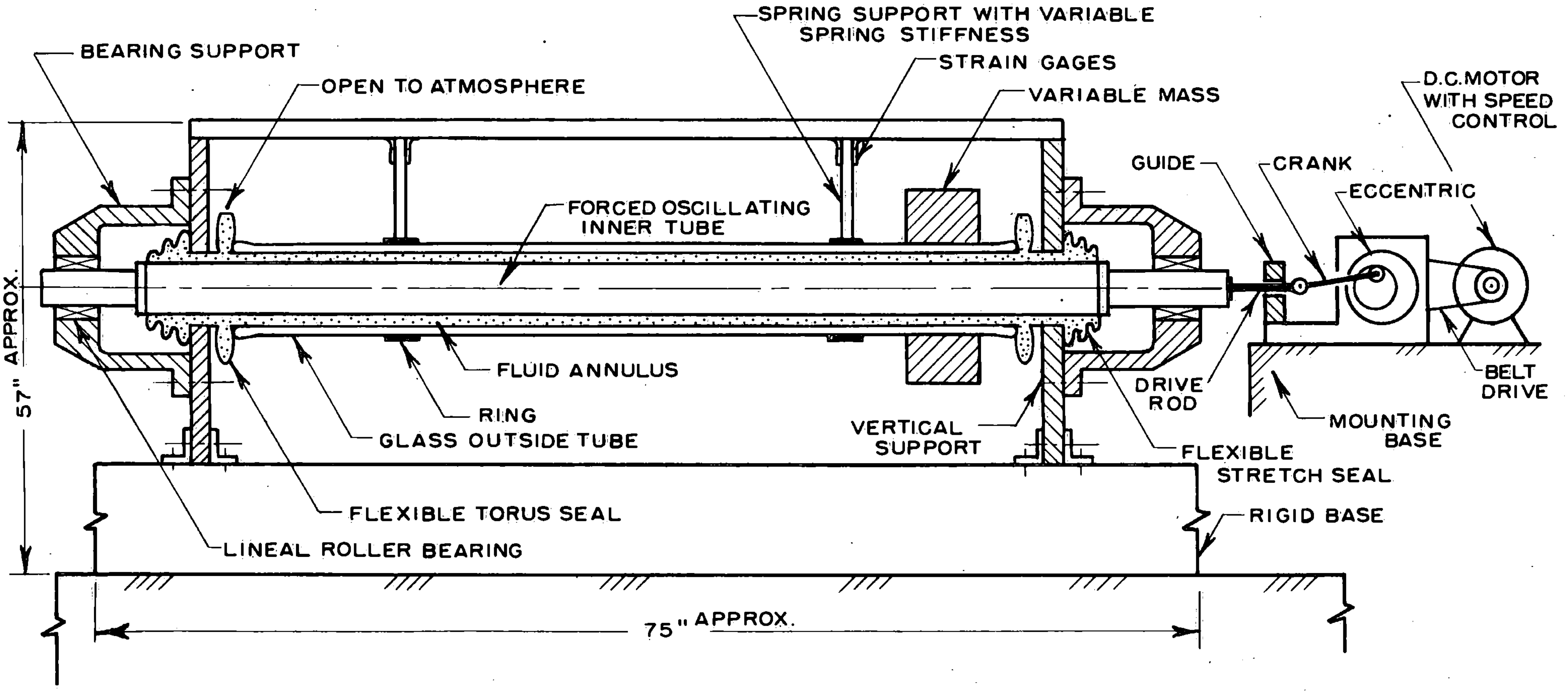

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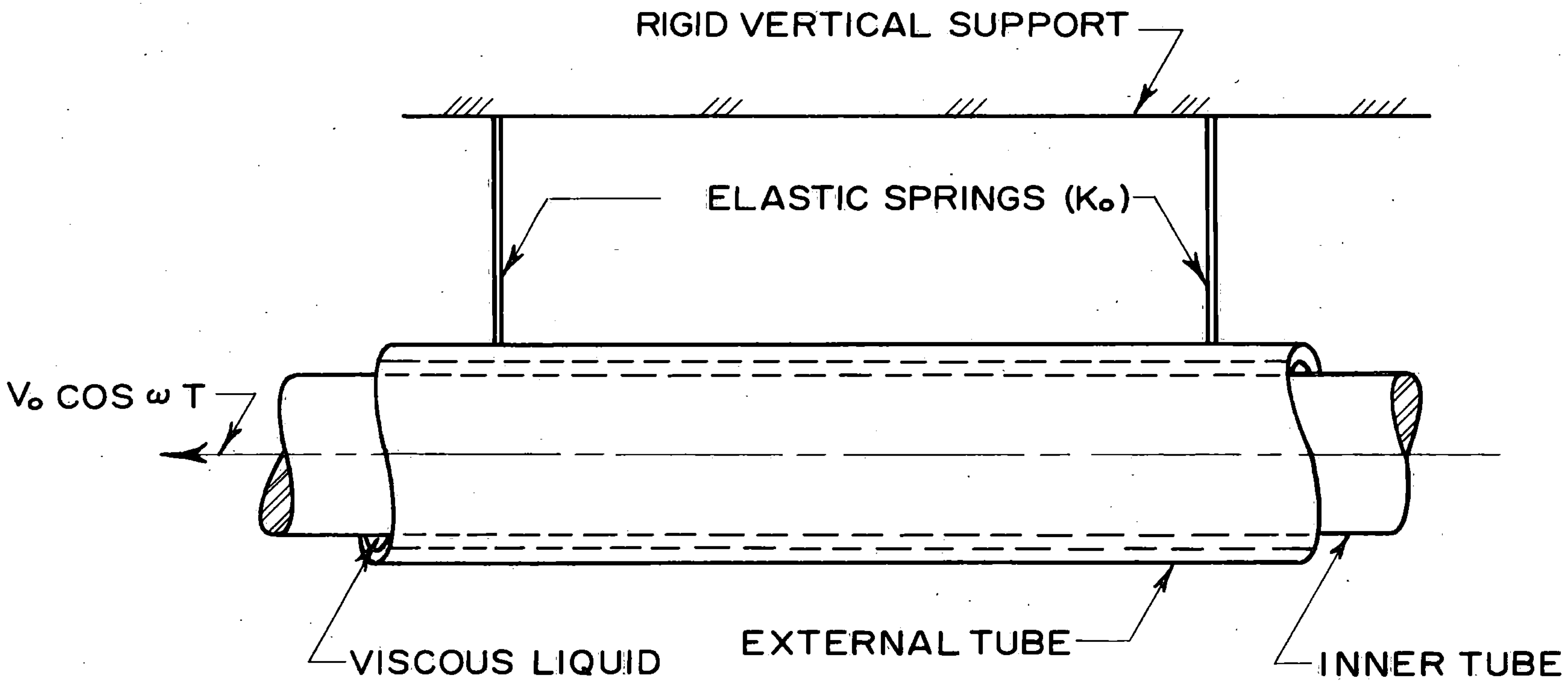
FIGURE I



SCHEMATIC OF CO-AXIAL LINEAR OSCILLATING TUBE FLUID FLOW GENERATOR

FIGURE 2

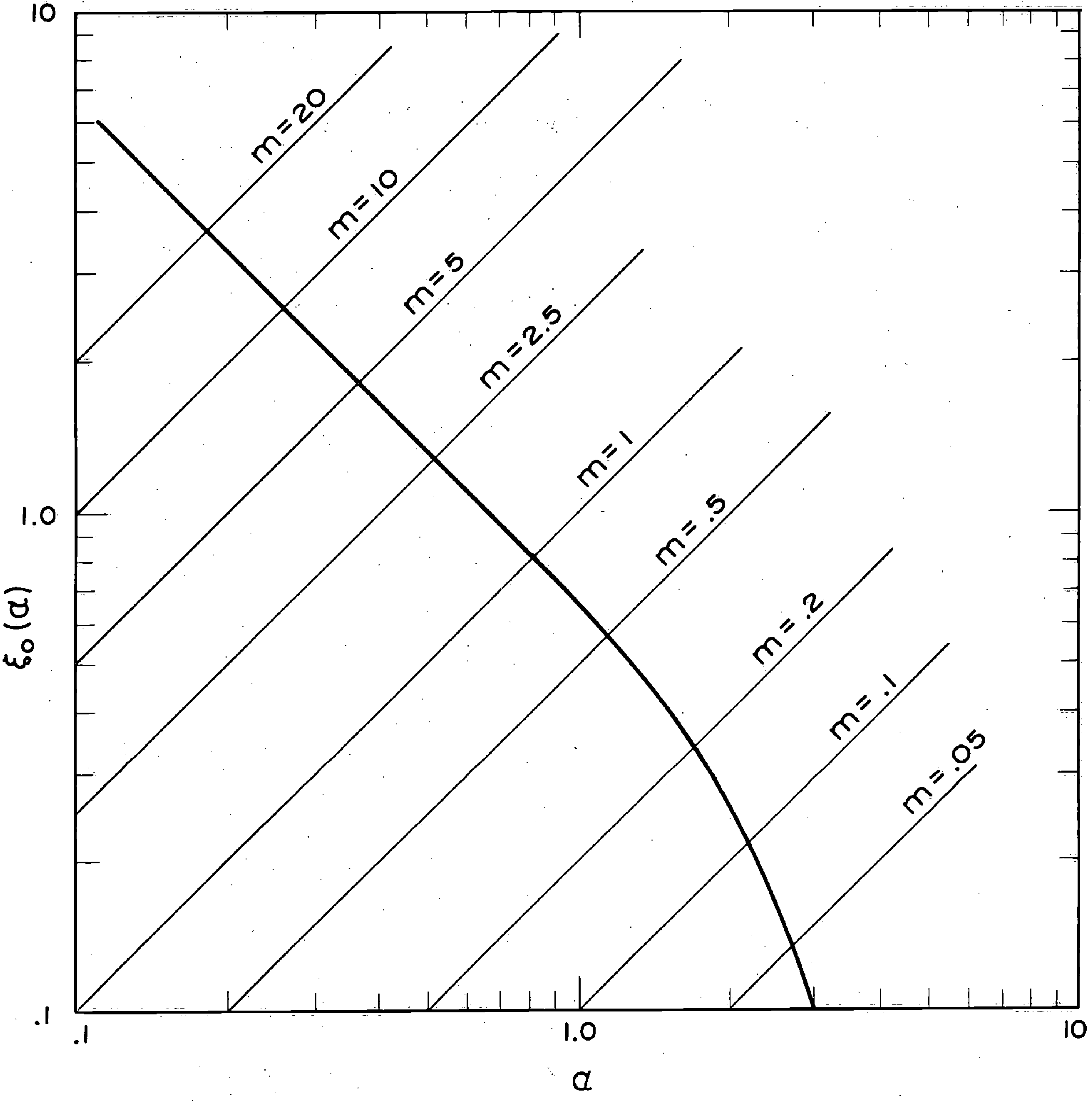


FIGURE 3

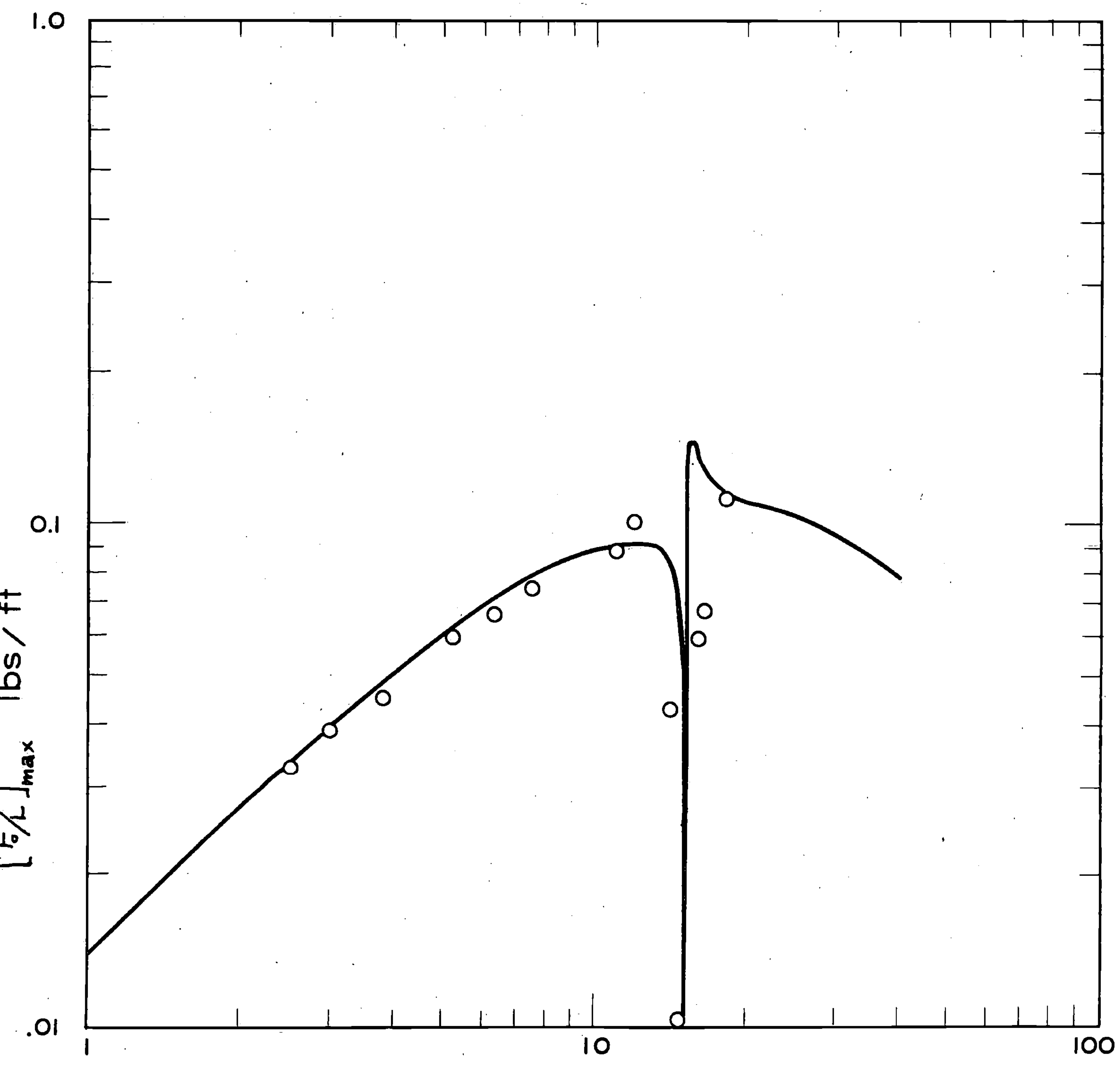


FIGURE 4

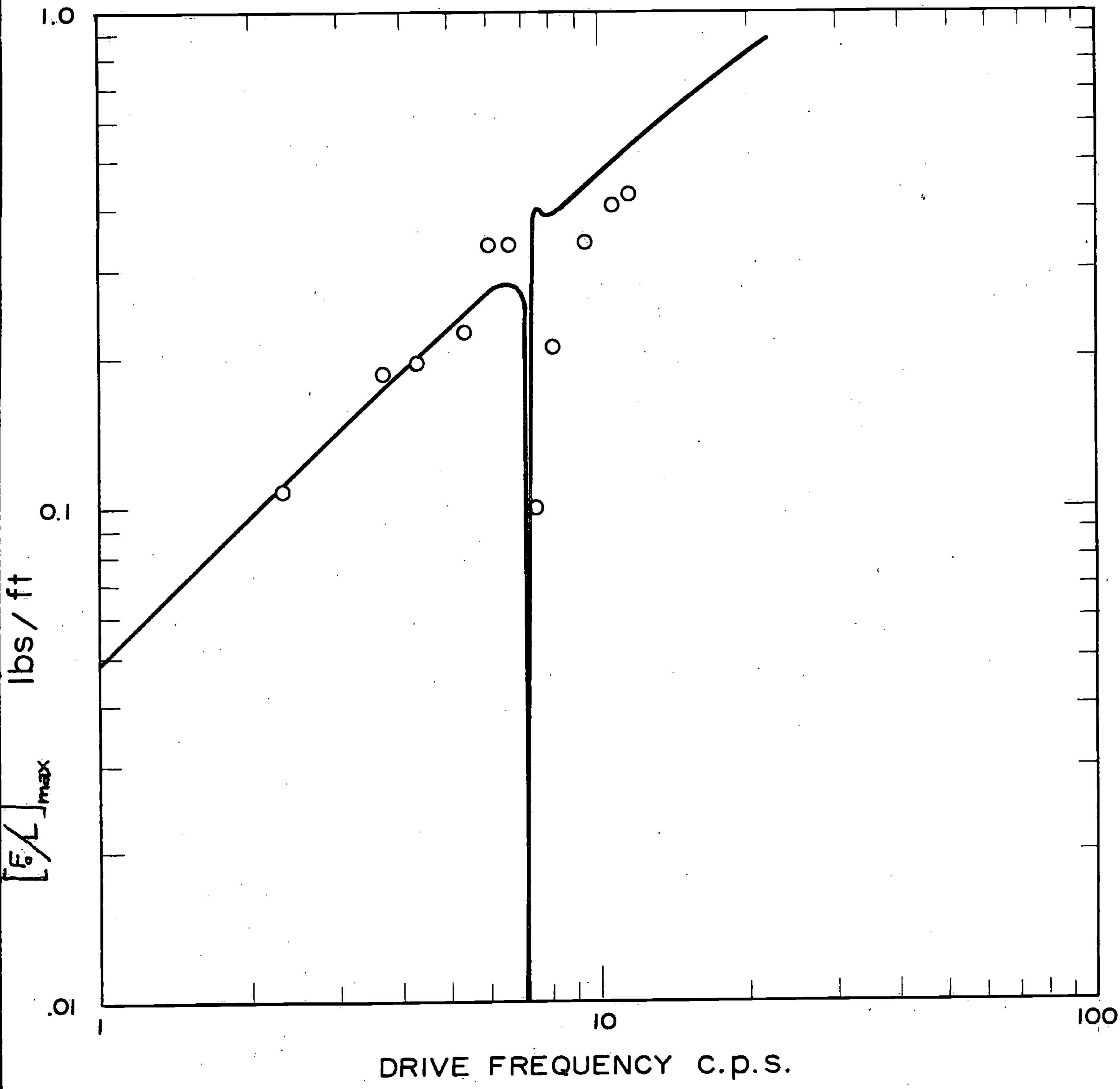


FIGURE 5

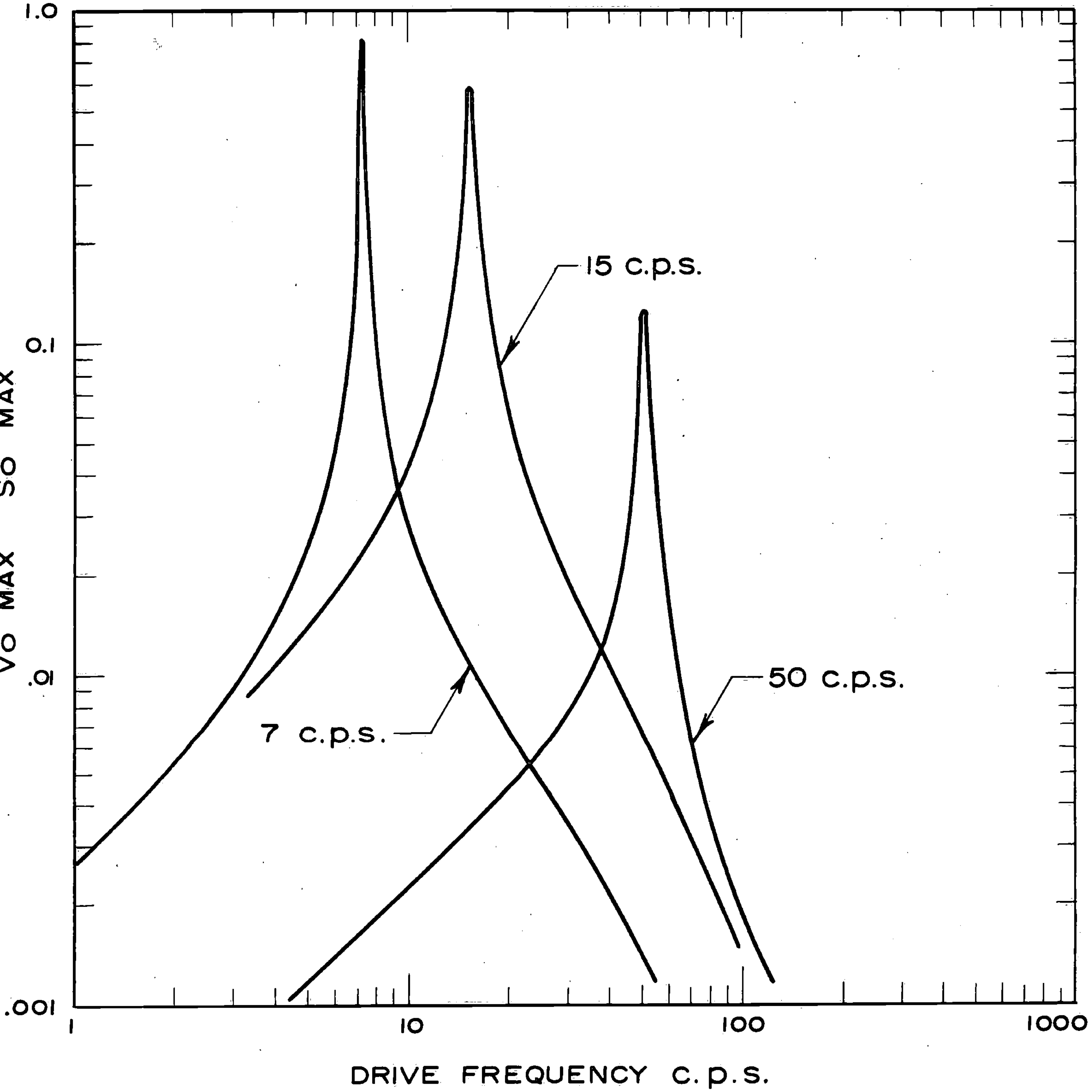

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FIGURE 6

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