EXCITATION OF LONGITUDINAL OSCILLATIONS IN A ROD BY HIGH-DENSITY CURRENT PULSES

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Results are given here on the excitation of steel, titanium, and tantalum end-loaded rods by the passage of current pulses of density 0.7–2.6 A/cm^2 and duration less than a quarter cycle of the free vibration of the rod. It is found that thermoelastic forces produce most of the excitation. The amplitude and frequency of the oscillations have been measured for various current densities, as has the energy supplied to the rod. The elastic modulus as a function of temperature is calculated for the range 270–2150° C.

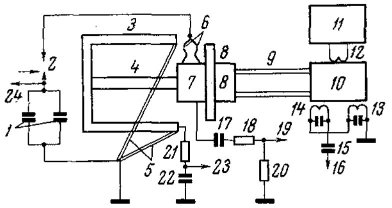

Fig. 1

1. The pinch effect produces radial compression of a conductor carrying a current. The pressure (N/m^2) is as follows [1] if the current I (A) is uniformly distributed over the cross section (radius r, in meters):

$$p = 10^{-7} I^2 / \pi r^2 \ . \tag{1.1}$$

If one end is clamped and the other is free*, a pulse of adequate amplitude and duration τ less than one cycle T of the free longitudinal oscillations will produce such oscillations by radial compression and thermoelastic forces. If $M > m$, the period of these oscillations is [2]

$$T = 2\pi \left((M + {}^1/_3 m)\, l / Es \right)^{1/2}, \tag{1.2}$$

in which m is the mass of the rod, l is the length, and s is the area of cross section, while E is the elastic modulus. The amplitude increases as τ is reduced from T to T/4, and relaxation during the pulse can be neglected for $\tau < T/4$, i.e., such a pulse may be considered instantaneous.

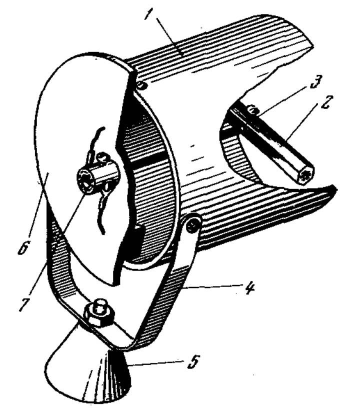

Fig. 2

Consider the relative amplitude $\varepsilon = \delta l$ of the motion produced by a pulse with $\tau < T/4$ in the absence of thermoelastic forces (only slight heating), on the assumption that $M \gg m$. The elastic energy of the deformed rod is taken equal to the kinetic energy of M to give

$$\varepsilon = v\,(M / Esl)^{1/2}, \quad v = \frac{s\mu}{M} \int_0^\tau p(t)\, dt \ , \tag{1.3}$$

*The free end bears a mass M, which serves to increase the period of oscillation and to connect the rod to the recording apparatus.

in which μ is Poisson's ratio and v is the velocity of M at the end of the current pulse. The expression for p is derived from the conservation of momentum, on the assumption that the rod transmits to the load all the momentum from the electrodynamic forces.

We combine (1.1) and (1.3) to get

$$\varepsilon = \frac{\mu\beta}{10^7 \sqrt{EMls}}, \qquad \beta = \int_0^\tau I^2(t)\, dt, \tag{1.4}$$

in which β may be called the action integral for the current [3].

The amplitude produced by the thermoelastic forces alone is kt_*, in which k is the coefficient of linear expansion and t_* is the temperature rise produced by the current pulse.

In the real case, the total effect is determined by the physical parameters of the rod and by M and β. We may take as a criterion the ratio of the thermoelastic and electrodynamic forces averaged over T/4:

$$\alpha = \frac{10^7 kt_* ETs}{8\mu\beta}. \tag{1.5}$$

The tests were made with rods of various materials employed with pulses having $\tau < T/4$ and various densities. The results are used to derive the elastic modulus as a function of temperature.

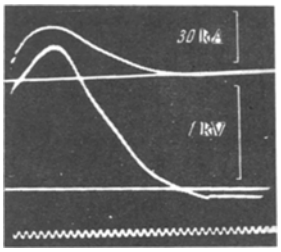

Fig. 3

2. The apparatus (Fig. 1) consisted of a pulse generator (two IM5-150 capacitors 1, power supply 24, and discharge gap 2), a current-measuring circuit, specimen holder 3, and a device for recording the longitudinal motion.

The current carried by leads 5 was determined by generating a voltage proportional to the rate of change of current and integrating this in RC circuit 21 and 22 (0.2 MΩ, 5600 pF), whose output passes to amplifier* I of an OK-17M oscilloscope. The resistance divider 18 and 20 (1.2 kΩ, 54Ω) is attached to the specimen via capacitor 17 (12 μF), and its output goes to input II of the oscilloscope.

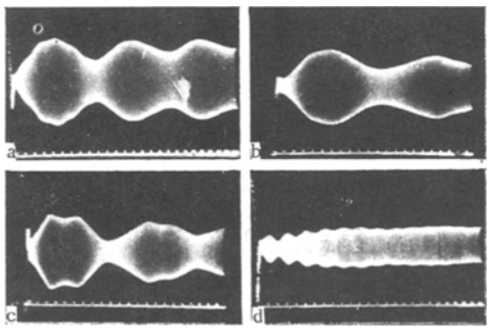

Fig. 4

*The plate loads of the output stages of amplifiers I and II in the OK-17M were raised to 2.4 and 2.8Ω, respectively, to increase the dynamic range and to match the amplifiers to the voltage sources; for the same reason, the input resistances were made 0.47 MΩ and 1 kΩ.

An induction system is used to measure the amplitude and period of the vibrations. This consists of the three coils 12, 13, and 14, with the ferrite core 10 (length 8 mm, diameter 7.9 mm) moving freely along the axis. This is rigidly linked via the duralumin tube 9 (length 79 mm, diameter 6 mm, wall 1 mm) and insulator 8 to the duralumin link 7, which is attached to the free end of rod 4 and to which run the two flexible copper leads 6 (length 100 mm, diameter 2 mm).

The parts attached to the free end of the rod had a total weight of 49.6, 51.3, and 42 g in the cases of titanium, tantalum, and stainless steel, respectively.

The primary coil 12 receives a 500 kHz signal from a 100-I11 oscillator. The secondary coils 13 and 14 are tuned to resonance and are connected so that their emfs are in opposition, being equal when the ferrite core is symmetrically placed. Any displacement of the core produces a net output from the transformer.

This transformer is screened in order to minimize pickup during the discharge of the bank of condensers. The output goes to the amplifier of input II of the OK-17M via the RC high-frequency filter 15 (5100 pF together with the input resistance of the amplifier), which heavily attenuates the fundamental in the discharge circuit (13.3 kHz).

The transformer coils each consist of 80 turns of PEV-2 wire 0.14 mm in diameter wound on a plexiglas former with an internal winding diameter of 12 mm, a winding width for each coil of 2 mm, and a distance of 2 mm between coils. A displacement of 0.1 mm of the core causes a beam deflection (double amplitude) of 10 mm on the screen of the OK-17M. The response is linear for displacements up to 0.75 mm.

The specimen holder (Fig. 2) is a horizontal duralumin tube 1 (85 mm diameter, 5 mm wall, 95 mm long), with the hexagonal brass rod 2 (thickness 14 mm) placed along a diameter at one end. The specimen 3 is attached to the center of this rod. The other end of the tube is attached to two copper leads, which go to one end of the capacitor bank 5. This end of the tube also has plexiglas disk 6 with a guide hole in the center. Thus the system is symmetrical with respect to passage of the current, which flows from the link 7 along the rod, which lies along the axis of the tube. The current branches at the brass rod and returns along the tube. A symmetrical design for holder is necessary to eliminate electrodynamic forces that would tend to tear the rod from the clamps.

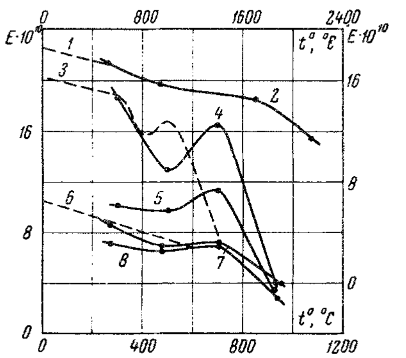

Fig. 5

The heavy current pulses are provided by discharging a capacitor bank (capacity 300 μF, inductance 0.47 μH) via a triggered gap having graphite electrodes.

3. The tests were conducted with round rods (pieces of wire) 98 mm long with the diameters 2r and masses m given at the top of the next column:

		2r, mm	m, g
Stainless steel	1Cr18Ni9Ti	1.59	1.56
Titanium	BT1-1	1.96	1.30
Tantalum	Ta 99.3%	1.51	2.66

The tests were performed in air under normal conditions with annealed and unannealed specimens, starting with the lowest discharge voltage V_0. The annealing was performed at 800° C in air for 1 hr, with subsequent slow cooling. Before each test, the transformer was moved on its carriage to the position of zero output.

Table 1

V_0	ε_*'	ε_*''	T'	T''	I_m	Q	t°
Stainless steel							
1.5	0.121	0.336	655	905	16.3	249	300
2.0	0.186	0.278	801	920	23.3	467	502
2.5	0.146	0.156	710	853	27.2	736	700
3.0	0.205	0.330	1440	1560	35.2	1090	930
Titanium							
1.5	0.23	0.368	860	945	20.9	214	273
2.0	0.227	0.395	970	995	28.7	434	496
2.5	0.130	0.220	950	962	34.4	713	707
3.0	0.150	0.280	1270	1480	37.7	989	939
Unannealed tantalum							
1.5	0.221		805		24.6	191	520
2.0	0.222		850		33.1	364	941
2.5	0.167		885		39.0	656	1700
3.0	0.182		995		46.8	991	2150

As only a single OK-17M oscilloscope was used, the current and voltage waveforms were recorded in turn. First the oscillations were recorded (3–5 times), and then the current and voltage. As the metal is partly annealed by the shock heating, a fresh specimen was used for each test with the unannealed material. Table 1 gives the results, where I_m (kA) is the peak current, t° is the temperature of the specimen (°C), T' and T" are the periods of oscillation (μsec) of the unannealed and annealed specimens, V_0 is the discharge voltage (kV), Q is the energy supplied to the specimen (J), and ε_*' and ε_*'' (%) are the amplitudes of oscillation of the unannealed and annealed specimens.

Figure 3 shows current and voltage curves recorded with stainless steel at V_0 = 3kV (current at the top, 500 kHz time marker). In this case the discharge was aperiodic; the same was true for the tests with tantalum and titanium. The lengths of the current pulses for stainless steel, tantalum, and titanium were 42, 38, and 36 μsec, respectively. Q was found by numerical integration [4] of the relation

$$Q = \int_0^\tau I(t)\, V(t)\, dt - \frac{LI^2(\tau)}{2}, \tag{3.1}$$

in which I(t) and V(t) are the current in the specimen and the potential difference across it, while L is the inductance of the specimen. Q was measured to 10%.

The temperatures for Ta and Ti were calculated from the temperature dependence of the specific heat [5]. For stainless steel, the value of [6] was used for the specific heat at 20° C (0.12 cal/g deg). while the temperature dependence was taken to be the same as for iron.

Figure 4 shows oscillograms of the longitudinal oscillations: a) annealed 1Cr18Ni9Ti steel at V_0 = 1.5 kV; b) unannealed VT1-1 titanium at V_0 = 2 kV; c) unannealed tantalum at V_0 = 2.0 kV; d) annealed tantalum at V_0 = 2.5 kV (time marks at 100 μsec). The first wave for the steel rod has superimposed on it the vibration of the

Table 2

Metal	$k10^6$	μ	kt_*, %	$\frac{1}{2}\varepsilon_*$, %	β, a^2 sec	α
Steel	16.6	0.291	0.465	0.06	1490	1000
Titanium	8.5	0.32	0.165	0.12	7250	200
Tantalum	6.5	0.3	0.325	0.11	12030	274

duralumin tube (period 200 μsec). The oscillation of the tube was most pronounced in the tests with annealed tantalum (Fig. 4d), where it was so large that it was impossible to measure the amplitude and period for the oscillation of the rod. The recordings were processed to give the duration T of the first cycle and the amplitude ε_* of oscillation (relative to the initial state) as functions of V_0. The amplitude was measured at T/2 after the start, and the metal ceases to be loaded at T/4, so this ε_* is twice the amplitude relative to the stationary state of the heated rod. The relative standard deviation of T was 2%, while that of ε_* was 6.5%.

Table 1 shows that ε_* varies in a complicated way with V_0. In some instances, ε_* at first decreases as V_0 increases, which is ascribed to increasing plastic deformation. Table 2 gives α, β, the measured amplitude $\varepsilon_*/2$, and the calculated amplitude kt_* for the unannealed rods with V_0 = 1.5 kV. It is clear that the calculated amplitudes exceed the measured ones, evidently on account of plastic deformation and curvature of the rods.

The α given by (1.5) lie between 200 and 1000, so the rod is excited almost entirely by thermoelastic forces. The highest current density (Table 1) was 2.6 kA/cm^2 (tantalum), while the lowest was 0.7 kA/cm^2 (titanium).

Figure 5 shows the elastic modulus (N/m^2) as a function of temperature as calculated from (1.2) in conjunction with Table 1, as well as the published values: 1) Ta [8]; 2) unannealed Ta; 3) 1Cr18Ni9Ti steel [7]; 4) unannealed 1Cr18Ni9Ti; 5) annealed 1Cr18Ni9Ti; 6) Ti [8]; 7) unannealed VT1-1 titanium; 8) annealed VT1-1. The coordinate axes for cuves 1 and 2 are upward and to the right, while for the other curves they are downward and to the left.

This method gives access to E at temperatures not accessible by other methods. The curves have the following features: 1) E for the unannealed metal is higher than E for the annealed metal; 2) some of the results (steel at t° < 400° C, Ta at t° = 520° C, Ti at t° < < 500° C) agree with published values, whereas others (steel at t° > > 400° C, Ti at t° > 500° C) differ substantially from the latter. For instance, the peak on the curve for stainless steel is displaced over 200° C toward higher temperatures. It may be that the cause of this discrepancy is error in measuring the temperature, though in that case the error would exceed the error of measurement. The relatively large (10–15%) error in determining the temperature arose because the present study was directed mainly to the excitation mechanism, not to precise measurement of E as a function of temperature. The temperature should be measured directly in such measurements, e. g., by optical pyrometry [9, 10].

The pulse length could be reduced by an order of magnitude [11, 12] by including in the circuit some copper wires whose cross section is less than that of the rod, and whose length is such that the interruption in the current is not less than two or three cycles of vibration of the rod.

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