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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 291

MEASURING VIBRATION AND TORQUE WITH THE OSCILLOGRAPH.

By R. Elsässer.

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MEASURING VIBRATION AND TORQUE WITH THE OSCILLOGRAPH.*

By R. Elsässer.

The recent development of technical science demands maximum reliability of functioning, together with maximum utilization of construction materials. For this purpose, we must know what stresses are produced during the functioning. One cause of great stresses is the mechanical vibrations, which only in rare cases can be accurately calculated and which, on account of the difficulty of observing and measuring them, receive much too little attention. Comparable observations are few and, in part, of doubtful value. There are but few technically utilizable methods of experimentation and they all require special and expensive apparatus.

The method here described is accurate and inexpensive, though dependent on the use of an oscillograph. Since, however, this instrument is already much used, on account of its excellent properties, for recording rapidly changing phenomena, it can be employed in many cases without any considerable expense.

The following conditions must be observed, in order to obtain satisfactory results when the vibrations are rapid.

1. The vibrations must not be noticeably affected by the recording apparatus. Hence no instruments with large masses, which

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* From "Zeitschrift des Vereines Deutscher Ingenieure," May 17, 1924, pp. 485-491.

damp the vibrations, can be employed.

2. The recording device must register the vibrations transmitted to it without appreciable diminution and shifting of the phases.*

The vibration period and damping of the recording device determine its accuracy. The smaller the vibration period and hence the larger the vibration number, the more accurate will be the recording of rapid vibrations. If the recording instrument has an appreciable mass and a long vibration period and is not damped, false curves will be recorded, especially for vibrations of abrupt wave-form. Such records have recently been published and have resulted in a number of further computations, which have given wrong results, because the curves employed, due to the fault of the recording apparatus, did not represent what they were supposed to.

The vibration numbers may be very large. If, for example, an electric motor with 3000 R.P.M. drives a machine over a pinion with 20 teeth which do not work smoothly, so that every tooth causes a jolt, there is produced a vibration number of 1000 r.p.s. in the motor shaft and, under unfavorable circumstances, with vibrations of considerable amplitude. In order to record such vibrations with sufficient accuracy, we need a recording instrument whose own vibration number is considerably larger and which does not damp the vibrations recorded. These conditions cannot be fulfilled by mechanical recording devices. On the contrary, we possess, in the oscillograph, an instrument which satisfies all requirements and even

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* Every freely oscillating recording device gives some error in amplitude and phase.

renders it possible to record several phenomena simultaneously. The essential part of the oscillograph, the so-called "Mess-schleife" (loop) is contained thrice in the chiefly used Siemens and Halske apparatus. Similar apparatus has recently been constructed with as many as six loops. Normal loops are made for vibration numbers of
12000 6000 3000 2000 per second and
with sensitivities of 0.005 0.003 0.0004 0.00007 per mm deflection. The maximum permissible deflection is 40 mm (1.57 in.) in either direction. The device for unrolling a paper strip, with which records of any length may be made, is especially suitable for vibration phenomena.

In order to record vibrations, still another device is required to convert the longitudinal or torsional vibrations, in a simple and direct manner, into electrical values which can be recorded by the oscillograph, without disturbing the vibrating system. Such a device may be created with the Kirchhoff-Wheatstone bridge. In Fig. 1, ab and cd are similar resistance wires, joined at their terminals to some external source of electricity, so that the current can be kept equal in the two wires, which are of exactly the same length. e and f are two sliding contacts, which are insulated from each other and rigidly attached to a connecting piece, so that when the latter is turned, they will slide on circular wires. These contacts are connected through resistances, with the loop of the oscillograph. Fig. 2 shows the arrangement for longitudinal vibrations. Here a second insulated wire is parallel to ab and cd at a short distance, both parallel wires being connected with the loop s. The sliding contacts e and f, each of which connects a test wire with a parallel wire, are insulated and attached to a rigid connecting bar, but have no current conductor. They function as follows:

The resistance of the wires is proportional to their length. If the current is constant, the tension is proportional to the length of the wire from which it is taken. If both sliding contacts stand exactly in the middle of the resistance of the two wires,* the bridge ef has no electric tension and consequently no electricity flows through it. Both these contact points of the wires are points of zero voltage. The voltage changes along the wire with the distance from the zero points according to Fig. 3, in which the horizontal line $-\varphi + \varphi$ represents the zero line of electric tension or voltage and the distance from the zero point, while the diagonals give the tension of each point of the wires in comparison with the zero point. Since, by moving the sliding contacts, the portion of the wire passed over is proportional to the displacement or angle of displacement, but the current in the loop is proportional to the tension at the points e and f, the deflection of the loop gives an accurate measurement of the displacement or displacement angle; provided, however, that the current in the test wires remains constant and that consequently the current in the bridge is small in

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* For practical purposes, it is neither necessary for the two wires to be of exactly the same length, nor for the sliding contacts to stand exactly in the middle. It is only necessary for them to be so adjusted that, in the position of rest, the bridge has no current and the loop shows no deflection.

comparison with that in the test wires. This adjustment is easily maintained, since the current in the bridge, according to the loop employed, is at most 0.003 to 0.1 ampere, which, however, is 25 to 100 times as large in the wire. If W is the resistance of the unit length of the resistance wire, D the distance of the contact point from the zero point and J the current in each measuring wire, then the tension of the bridge, corresponding to the displacement D, is $e = 2\ WDJ$ and the current in the loop is

$$i_s = \frac{1}{\rho} \times 2\ WDJ,$$

in which ρ is the resistance of the circular wire. For a uniform wire of 0.5 mm (0.02 in.) diameter, the resistance for a length of 1 mm (0.04 in.) is $\frac{2.44}{1000} = 0.00244$ ohm. The current intensity can be one ampere. If $\rho = 5$ ohms, then

$$i_s = \frac{2}{5} \times 0.00244 \times 1 \times 1 = 0.00098 \text{ ampere}$$

for 1 mm displacement of the sliding contacts. With a loop having a sensitivity of 0.00007, we therefore obtain, for 1 mm displacement, a deflection of 14 mm (0.55 in.) in the oscillograph. For a wire of 1 mm (0.04 in.) diameter, the corresponding values are $W = \frac{0.61}{1000} = 0.00061$ ohm and $J =$ about 3 amperes. With $\rho = 5$ ohms, $i_s = \frac{73.5}{100000} = 0.000735$ ampere and the deflection will be about 10.5 mm (0.41 in.) for 1 mm (0.04 in.) displacement. Hence, very small rotation angles can be thus measured. If, for example, the test wire has a curve with a radius of 200 mm (7.87 in.), a rotation angle of 1° then corresponds, on the wire, to a displacement of

3.49 mm (0.137 in.) of the sliding contact which gives, for the abovementioned relations, a deflection of 49 mm (1.93 in.) in the oscillograph. Since 0.5 mm (0.02 in.) can still be accurately read, a rotation angle of 0.01° can here be accurately measured. As will subsequently be shown, transmission gearing can be introduced between the shaft and the sliding contact, which will still further increase the sensitivity. Due to the small voltage, it is necessary for the sliding contacts to be good and uniform (which is easily accomplished by sufficient pressure and light lubrication) and for all contacts in the circle to be in good condition. For larger displacements, the deflection of the loop can be reduced to any desired scale by the use of less sensitive loops and the introduction of resistance coils into the sliding contact circuit.

The curves recorded by the oscillograph with the above described apparatus are diagrams of the distance or of the angle in terms of the time. The time unit may be changed at will by changing the revolution speed of the oscillograph drum. In certain cases, it might also be possible to record acceleration curves directly by the use of some such device as the one contained in the accelerometer of Siemens and Halske. Due to the sharpness and the large scale of the path-time-curves obtained with the regular arrangement, there is usually no difficulty, however, in plotting the speed and acceleration curves.

The employment of the switch for longitudinal vibrations is very simple. The test wires are attached to one of the parts vibrating opposite one another and, if necessary, close together. Both sliding contacts, insulated from the other part, are then attached. They preferably consist of thin but hard sheet metal. Some device is necessary for adjusting the zero point. It must be possible either to adjust the sliding contacts separately or to vary the length of the wires through which the current flows. The approximate equality of the currents in the two arms can be easily verified with a millivoltmeter and a device consisting of two parallel wires. This verification is not necessary, if both test wires have the same diameter and length and the connections are well soldered.

Figs. 4-7 are records made with the above described apparatus on a Siemens-Schukert drilling machine (Fig. 8). This consists of a rigid housing with a motor, which drives a sliding car inside the housing by means of transmission gearing and a slot and crank drive. In the sliding there sits, between two strong, initially stressed spiral springs, the piston and piston rod carried by the drill and free to oscillate with the springs. Fig. 8 shows how simple the whole arrangement is. The two wire bridges of 1 mm (0.04 in.) resistance wire and like parallel wires were connected in series, so that equal currents of 5 amperes (2.5 in each branch) flowed through both. All connections were soldered and the cross-connections of the bridge were of thick copper, so that their resistance was very small in comparison with that of the test wires. The latter were tensible, so that they could be kept constantly taut. Each of the sheet-copper sliding contacts could be moved separately. The middle of the slide-way (with the crank vertical) was taken as the zero position of the car. There were recorded: the distance of the car from the housing (curve a); of the piston from the car (curve b); and the current in a conductor to the three-phase motor (curve c) which also furnished the time unit, the interval between two adjoining current peaks being 0.02 second. Figs. 4-6 are records with a heavy drill, with the fly-wheel removed and with an increased number of blows, with weak, normal and strong thrust. The piston deflections were largest with a weak thrust and smallest with normal thrust. Fig. 7 gives the curves for a machine in normal running condition. All the records were made with drills in stone of medium hardness and produced a picture of the actual stressing of the materials, which could be obtained in no other way. The units of measure are the same in all the records, but those for the b curves are different from those for the a curves. The unit of measure for such records was determined by moving the parts, in a machine at rest, an exact measurable distance and making a short record under this condition.

Figs. 9-11 are records made on a Siemens-Schukert oscillating sliding drive. This consisted of a three-phase motor (3.5 kilowatt), which drove, by means of transmission gearing, a crank with a connecting rod. The cross-head oscillated about pins which were held in two flanges riveted to the sliding metal sheet. The connecting rod passed freely through the cross-head and was connected with it on both sides by spiral springs, whose tension could be varied by means of flange nuts. The car, which ran on rollers on circular tracks, was also free to oscillate. The length of the sheet-metal track was 40 m (131.2 ft.); the weight of the moving parts 1240 kg (2734 lb.); the added load 3000 kg (6614 lb.). Records were made:

1. Of the vertical motion, curve a, Figs. 10-11;
2. Of the horizontal motion, curve b, Fig. 11.

A test wire was fastened on each side of the chute, to insulated U-irons beaten into the ground and freely extended. The sliding contacts were attached to the chute;

3. Of the motion of the connecting rod with respect to the sheet-metal of the chute, curve c. The three wire systems of 1 mm (0.04 in.) resistance wire were connected in series, each wire carrying 2.5 amperes;
4. Of the motion of the material with respect to the chute (Fig. 9, curve d). The wires were stretched on a wooden frame on the sheet-metal chute, the sliding contacts on a largerflat piece of material, which lay in the middle of the other material and passed with it under the wooden frame;
5. Of the current in a conductor leading to the motor which simultaneously gave the time unit (curve J).

The conducting wires from the measuring bridges to the oscillograph were, in this case, connected with three rows of six mercury cups each and the three corresponding pairs of plugs were connected with the three loops. This rendered it possible, under like working conditions, to record three different sets of curves within a few seconds. Fig. 9 shows a record of the stator current, of the motion of the chute with reference to the connecting rod and of the material with reference to the chute. In curve d, the material was at rest with relation to the chute, so long as the curves ran parallel to the zero line. The distance of the material was approximately equal to the vertical distance between the parallel portions of the curves. In this record (Fig. 2), the loops passed through the sliding contacts, from the points a and d through the zero point, to the points b and c. The curve began therefore with the maximum negative deflection and ended with the maximum positive deflection. The manner of working, as shown by Figs. 10-11, was the following: On every revolution of the crank, the sheet-metal, together with the material lying on it, when the maximum speed was nearly reached, was moved quickly forward. The sheet-metal was strongly retarded and carried backward and below, while the material, accelerated with the sheet-metal due to its inertia, retained its direction of motion and its elevated position for a time. As soon as the material again came in contact with the sheet-metal, the motion of the latter was strongly retarded (whence the slight depression of curve c) and was again carried with it. Fig. 10 shows the vertical motion of the sheet-metal with reference to the ground (curve a); of the connecting rod with reference to the sheet-metal (curve c); and the current record of the engine (curve J). In Fig. 11, the motion of the sheet-metal parallel to the ground is shown instead of the current. The three records correspond to different loads and spring tensions and are therefore not directly comparable. They were taken from a long series of records. It is remarkable that, both in these records and in those with the drilling machine, in spite of the very strong jolts which necessarily occurred, the curves are perfectly clear and definite.

Two methods may be employed for recording rotary oscillations: either the measurement of the relative velocity of the cross-section of the shaft with respect to a constant angular velocity of the rotating object or the measurement of the mutual distortion of two separate cross-sections of the elastic transmission rod. The Wheatstone bridge may be used in both methods. For measuring the distortion of two cross-sections, the test-wires are connected with one cross-section and the sliding contacts of the bridge with the other. For shafts, it is necessary for the distortion of a cross-section to be applied by a rigid tube fastened only to this cross-section and extended to the other cross-section, as already described by Föttinger ("Forschungsarbeiten," No. 25). An insulated support rigidly attached to the free end of the tube holds the sliding contacts, light knife-shaped metal plates, easily moved in the radial direction but immovable in the peripheral direction. They are held against the test wires by springs or light centrifugal weights. The support for the test wires is fastened to the second cross-section of the shaft. Since, in general, only small arcs are swept by the sliding contacts, it is necessary to have only a narrow flat support with shallow grooves on its circular perimeter for receiving the resistance wires. It may consist of insulating substances (wood, hard rubber, fiber, etc.) or of metal. In the latter case, the test wires, which must be taut, have some insulating support like thin mica. Since only very small tensions, of not more than two volts, arise, the insulation occasions no difficulty. Lastly, two insulated sliding rings must be employed for delivering the current to the test wires and also for carrying the bridge current, two of which are connected with the nodes ac and bd in Fig. 1, and both the others with the sliding contacts. The sliding rings may be applied to any part of the shaft. Since only very small distortions come into question, the electrical connection of the sliding rings with the test-points may be made with the simplest means. If a very elastic coupling is available, the application of the measuring device will be still further simplified. For the exact adjustment of the zero point, the supports must be slightly adjustable.

The device may be constructed with very simple means and requires only very small masses for sureness in functioning and accuracy in measuring. The friction of the sliding contacts on the round test wires is negligible, even with relatively strong pressure. Likewise the friction of the brushes on the sliding rings can be kept very small, so that no noticeable damping results. On the other hand, it would be easy, should there be any occasion for it, to introduce any desired degree of damping between the two oppositely oscillating parts. Moreover, a high transformation of the angular distortion may be effected in a very simple manner, as will subsequently be more fully explained. Since the distortion of two cross-sections of a shaft or an elastic transmission member of a different kind is proportional to the transmitted torque, this device can record both constant and variable torques.

Fig. 12 is the longitudinal section of a torsion dynamometer of this kind without transformation, with which the following records (Figs. 13-19) were made. The whole apparatus, and especially the transmission tube, is very strongly built, in order to be able to withstand strong jolts without overloading the spring. On exceeding the permissible distortion, claw-like projections on the free end of the tube e push against corresponding projections on a replaceable ring r, which is screwed to the support of the test wires, and thereby switch out the torsional spring. a_1 and a_2 are tension rings for coupling with both the shaft journals. b_1 and b_2 are iron disks which are fitted to both the tension rings and in which the spring d is held stationary by wedge-bolts. To one of the iron disks is secured the test wire support, a wooden disk c of 350 mm (13.78 in.) diameter. The transmission tube e carries, on a paper collar f with clamping rings, both the supports g of the sliding contacts and the rings o for conducting the current from the bridge to the oscillograph. On the second tension ring, also on a paper collar h, rest the rings i for the current delivery. Heavy slotted pieces are soldered into the upper ends of the brass supports g. In the slots there move, without play, the copper contact edges k (to which are soldered thin sheet-metal pieces of the same material as the resistance wires), as the real sliding contacts. For better electrical connection of the contact knives with the carriers, both are bound by soldered flexible copper strips. The ball-bearing l serves for the centrifugal motion of both parts. The spring is 200 mm (7.87 in.) long between the wedge-bolts d and had, in the following experiments, a diameter of 10 mm (0.4 in.). It was made from special spring steel of 14500 kg/cm² (206241 lb./sq.in.) breaking strength. In the experiments, it was subjected to a torsional stress of 10 mkg (72.3 ft.-lb.), without affecting the zero position. The moment of inertia of the disk end, including a rod of 3 cm (1.18 in.) diameter and 45 cm (17.7 in.) length and two ball-bearings, was 0.122 cm^2-kg (0.042 lb.-sq.in.) while that of the other end was 0.025 cm^2-kg (0.0085 lb.-sq.in.). The vibration number of the spring with the disk end of the apparatus and the attached rod was found by computation to be 29.6 per second, as shown in Fig. 13.

For determining the vibration number, one end was stationary, while the other was turned with the coupled rod and held firmly by means of a strong cord drawn through a hole in the disk c. The cord was suddenly cut and the resulting oscillation number of 50 per second was recorded as the unit. Here, as in all the following records, a loop with a sensitivity of 0.0004 was used. Figs. 14-19 are records showing the accurate work of this apparatus and several noteworthy phenomena. All the records were taken with a three-phase motor with short-circuited rotor for 2.2 kilowatts, at 1420

R.P.M. with 36 stator slots, in which stators of different numbers of bars but the same mass of copper were inserted. The motor was loaded, in starting, only by the momentum of a rotating mass (brake drum brake lever 0.225 m (8.86 in.), moment of inertia 6.68 cm-kg^2 (2.28 lb.-sq.in.), on the end of the 3 cm (1.18 in.) shaft. After reaching the maximum revolution speed, a cable brake was applied until the engine was brought to a stop. It was then allowed to start again. Hence the curves show the starting from a position of rest with the tension removed from the shaft spring up to idling speed, then the gradual braking to a stop and starting again with spring under tension. Since similar elasticity relations occur in the usual method of driving by means of elastic transmission devices (belts, cogs, couplings, etc.) the phenomena here recorded occur also in practice. In the figures, the middle line is the zero line for all three curves. The upper curve gives the deflections of the torsion dynamometer and, since these are approximately equal to the transmitted torque, the upper line represents the torques which pass through the shaft. As in all dynamometers with mass and elasticity, the oscillation of the mass, which represents a pulsating torque, exceeds the variable moment proceeding from the motor. The curve of the torques is not, therefore, at least in its rapidly changing portions, the moment curve of the motor, as is often wrongly assumed, but it is the oscillation curve of the rotor-shaft-driven mass, consisting of subjective and objective vibrations, only the latter coming from the motor.

The curve below the zero line gives the angular velocity of the rotor or (since $\omega = \frac{\pi n}{30}$) the R.P.M. It is obtained as the voltage line of a small separately excited direct-current dynamo, whose overhanging armature (without bearing) is rigidly screwed to the shaft of the three-phase motor. The third curve, which shows oscillations on both sides of the zero line, is the current in a conductor leading to the motor.

Fig. 14 was obtained with a rotor A. The broad line of the moment curve is not due to a broad spot of light but to the superposition of vibrations of very small amplitude and high frequency. As a result of the high frequency, the motor shrieks with this rotor. Otherwise, the curve, aside from the starting wave, is continuous and entirely free from oscillations.

Fig. 15 is the curve of another rotor B. Here the curve also has a slight wave, but of much smaller frequency, superposed and with a slight unevenness at about 1/7 of the synchronous revolution speed. In the firmly braked position (with brake drum still) the moment of the torsion spring does not remain constant, but there arises a pure harmonic vibration with an amplitude 1.6 times the maximum motor moment and with a vibration number of 16.2 per second (the subjective or inherent vibration number of the undamped system being found by calculation to be 18 per second, with a brake drum). The inequalities in the wave heights are due to the fact that the brake was applied by hand by pulling on the brake cable, so that the force varied. These vibrations, in the firmly braked position, can be as long as desired and, with a constant brake moment, perfectly uniform. It may not be generally known that a motor of equality of circumferential force, like the three-phase motor, gives such vibrations, in working through an elastic transmission member, when the brake moment is greater than the torque of the motor. Since the forces arising in this connection attain nearly twice the value of the maximum torque, this phenomenon has an important bearing on the possible stressing of the material. The same effect of the elastic transmission appears in starting the motor, as shown by the illustrations, and thus overcomes the starting resistances, which would not otherwise be possible.

Fig. 16 gives the curves for a third rotor C. They were recorded at about 3/4 the normal voltage of the motor, while the other figures were obtained at the normal voltage. The number of bars of C is often employed for the sake of smooth functioning. In the first third of the revolution speed it gives unusually violent vibrations (which are naturally still more violent under full voltage), whose causes are strong fluctuations in the torque curve of the motor in this field. Under full terminal voltage, the deflections reach values amounting to more than 10 mkg (72.3 ft.-lb.), hence about seven times the normal torque. Of course such strong oscillations occur only when the power transmission is sufficiently elastic.

Fig. 17 was recorded with a specially constructed rotor. It shows smaller oscillations (hence very small irregularities of the torque curve) and a very high torque.

Fig. 18 gives the curves for still another rotor, which also produced strong oscillations, while Fig. 19 was obtained with a so-called "eddy-current armature," which gives a weak starting current and hence a small starting moment.

The oscillations are of the same nature as for the ordinary rotor (same number of bars, Fig. 16), but much smaller. It is characteristic that rotors with strong oscillations run quietly, while the ones with smooth curves shriek. The records show further that some bar numbers always give a smooth start while others produce a jerky effect.

As shown by the illustrations, the vibrations in a shaft and the torques can be easily and accurately recorded. For this purpose, it is only necessary to apply the graduated disk with the resistance coils to one cross-section of the shaft, to another cross-section the transmission tube and, at a suitable point, the sliding rings with the receiving brushes. Graduated disk, transmission tube and sliding rings can be distributed along the shaft, to which they must be secured as rigidly as possible. They can then be applied, in a few minutes, to any shaft it may be desired to test, without making any change in the shaft. The testing apparatus can be easily graduated for small shafts, by rigidly fastening one end of the shaft and loading the shaft (behind the section to be tested and by means of an accurately measured lever-arm) with a given torque. Since, with permissible load limits, the distortion is exactly proportional to the torque, only a single record is necessary. For larger shafts, the torque can be calculated with sufficient accuracy, when the modulus of shear S of the shaft material is known. The value of S varies only within very narrow limits. It is then necessary to find the distortion angle for a given deflection.

The angular distortion can be easily magnified. Föttinger has already done this with his torsion indicator. Such transformations can here be made much more simply, because all the levers move only in parallel planes. They may therefore rest on knife edges, where they are held by springs, so that no motion is lost. Such a conversion device is illustrated by Fig. 20. A is the shaft and B the transmission tube with two rigid arms C. The conversion lever D rests at L on the graduated disk, which carries the wire E bent concentrically to L. The contacts F slide on the wire arc E. The graduated disk is rigidly attached to the shaft.

For simply measuring the torque, no oscillograph is necessary, only a good millivoltmeter of high resistance being required. What small distances are here required is best illustrated by two examples. The test wires have a diameter of 1 mm (0.04 in.) with a conductivity of 0.5. The resistance of a length of one millimeter is 0.00061 ohm. The wire carries a current of 2.5 amperes, which it can permanently withstand. A regular millivoltmeter with 10 ohms resistance V was employed. The scale had 150 divisions amounting to 45 mv. Hence one division equaled 0.0003 volt.

<u>Ex. 1</u>.- A 5 cm (1.97 in.) shaft transmits a torque Q of 30 mkg (216.9 ft.-lb.). The distance L between the cross-sections of

the shaft is 50 cm (19.69 in.). The radius R of the arms of the transmission tube is 25 cm (9.85 in.). The conversion ratio u of the contact lever is 15:1. The modulus of shear S of the shaft material is 828,000 kg/cm^2 (11,776,900 lb/sq.in.). Then the deflection arc on the test wire (in mm) is

$$l = \frac{LRQ\ (\text{cm-kg})}{SI}\ u\ 10$$

in which I is the moment of inertia of the shaft cross-section (here 61.4 cm^4 = 1.48 in.^{4}). Hence

$$l = \frac{50 \times 25 \times 3000}{828{,}000 \times 61.4} \times 15 \times 10 = 11.1 \text{ mm } (0.437 \text{ in.}$$

For this deflection the electric tension at the sliding contacts is $e = 2 \times 0.00061 \times 11.1 \times 2.5 = 0.0339$ volt. This corresponds to a deflection of 113° on the millivoltmeter. One meter-kilogram would accordingly give a deflection of 3.77° and, since 0.1° can be read on such an instrument, a variation of 0.025 mkg (.18 ft.-lb.) in the torque can still be read. The employment of such low voltages is not uncommon in electrotechnics. Thermo-electric couples are extensively used with still lower voltages and attain a high degree of accuracy. It is nevertheless necessary to diminish the resistance in the bridge circuit to a small total, by carefully adjusting the sliding contacts and the brushes on the slide rings and keeping all the other contacts in good condition. The brushes must be metal and must be properly and securely adjusted and easily lubricated, as likewise the sliding contacts. The latter must function without lost motion. The last illustrations show that such was the case with the apparatus employed. The adjustment was not difficult.

Ex. 2.- A ship's shaft of 30 cm (11.81 in.) diameter has to transmit 2000 HP at 75 R.P.M., corresponding to a torque of 19,100 mkg (138,150 ft.-lb.). The distance between the cross-sections is 50 cm (19.7 in.). The radius of the arms of the transmission tube is 50 cm (19.7 in.). The conversion ratio of the contact arm is again 15:1 and the modulus of shear is 828,000 kg/cm² (11,776,900 lb./sq.in.). The deflection arc on the test wire is

$$l = \frac{50 \times 50 \times 1,900,000}{828,000 \times 79,525} \times 15 \times 10 = 11 \text{ mm } (0.43 \text{ in.})$$

The electric tension at the sliding contacts is therefore $e = 0.0335$ volt and the deflection of the millivoltmeter is 112°. It is possible to read a variation of 17 mkg (123 ft.-lb.) or about 0.1% of the HP.

The requisite space of 0.5 m (1.64 ft.) length and 1 m (3.28 ft.) diameter, is very modest for a 30 cm (11.8 in.) shaft, but, with a fairly well executed test, gives a high degree of accuracy (of the same order of magnitude as with a Wheatstone bridge) for resistance tests. The testing device can be firmly installed and the millivoltmeter graduated directly in mkg, if provision is made for keeping the test current constant. It is possible to accomplish this in a simple manner by employing two storage batteries or by taking the current from an electric lighting system with the introduction of iron-wire lamps. The test instrument may be installed at any desired distance from the point tested. The current-conducting wires may also be led to the same observation point and an ammeter and rheostat be installed, so that the current can be exactly regulated before each reading. Moreover, the same as for thermographs, the variations of the torque may be recorded and (by using additional pens) the torques of two or more shafts can be recorded simultaneously. The condition of the testing instrument may thus be determined at any time, by finding whether the pointer stands at zero with the shaft at rest, before the test current is turned on. If the modulus of elasticity of the shaft material is known (which is nearly always the case with large shafts), the graduation is extremely simple, since the millivoltmeter only needs to be graduated for angular distortion. The two sliding contacts are separated from the test wire by slipping a sheet of paper under them. The wires are then tested by means of two test-contacts, electrically connected with the sliding contacts, at a distance of about 1 cm (0.4 in.) from the zero position. The simple reading of the resulting deflection suffices, since both deflection and torque are proportional to the distance from the zero point.

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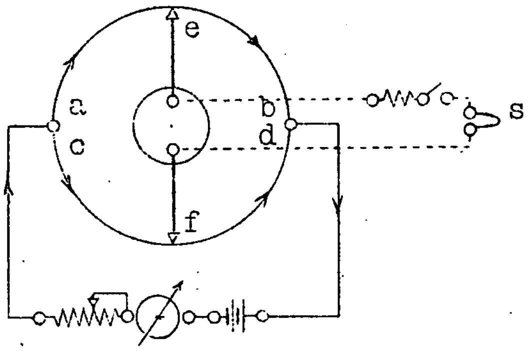


Fig. 1 Circuit for measuring distortion angles.

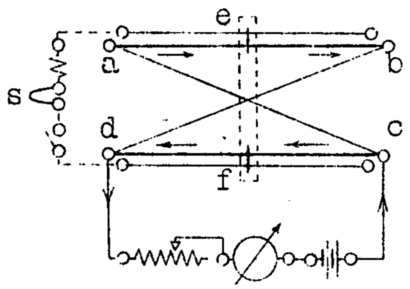


Fig. 2 Circuit for measuring longitudinal vibrations.

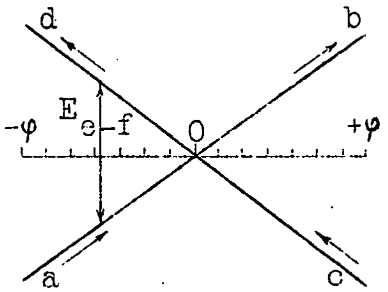


Fig. 3 Voltage diagram

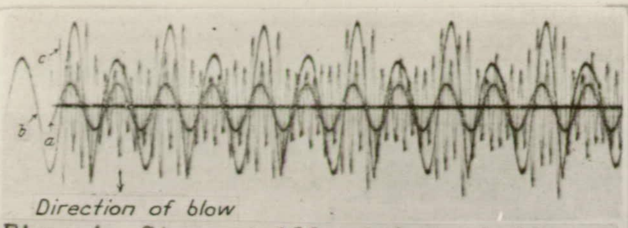


Fig. 4 Stone drill with weak thrust

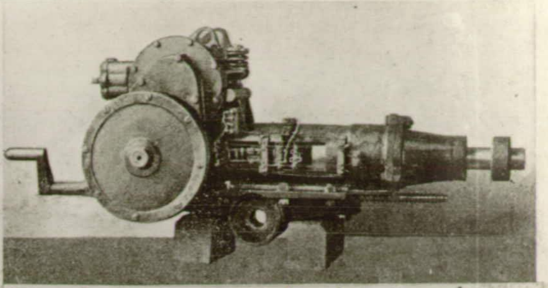


Fig.8 Siemens-Schuckertwerke drill with testing device

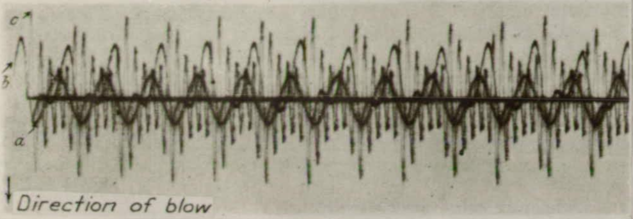


Fig. 5 Stone drill with normal thrust

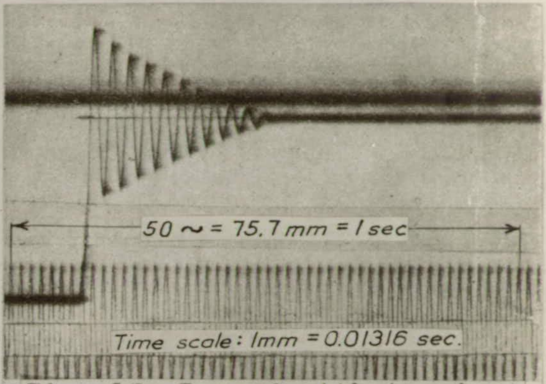


Fig. 13 Record with torsion dynamometer. Vibration of disk end

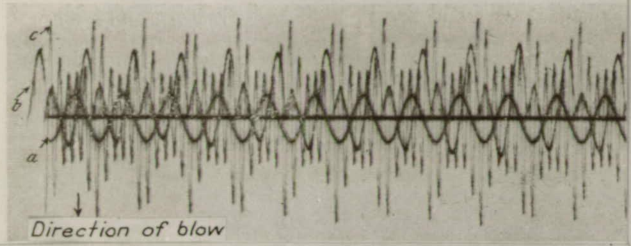


Fig. 6 Stone drill with strong thrust

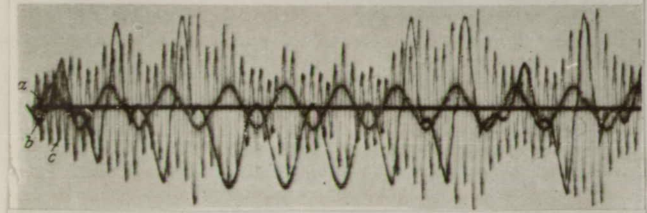


Fig. 7 Stone drill with jamming drill

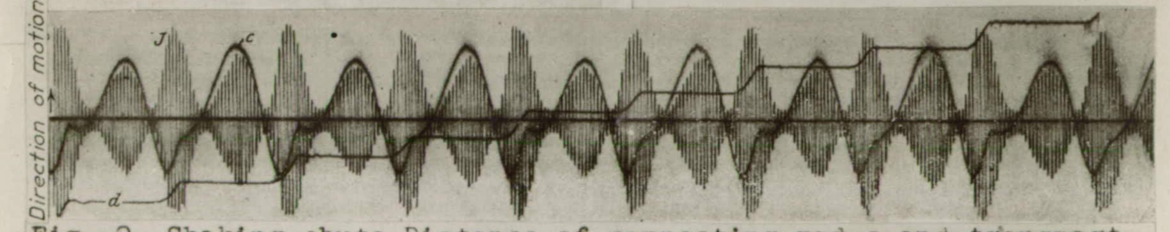
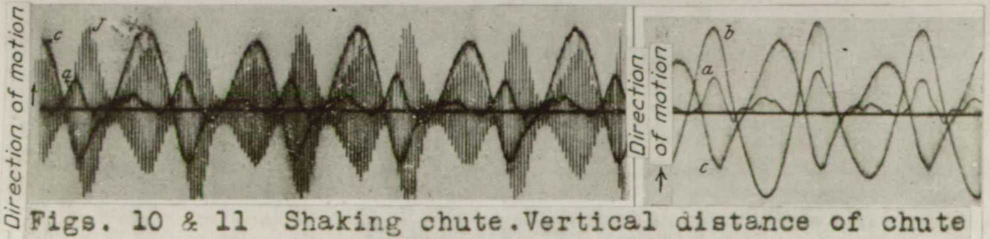


Fig. 9 Shaking chute. Distance of connecting-rod c, and transporting belt d, with respect to the chute metal. Motor current J



Figs. 10 & 11 Shaking chute. Vertical distance of chute from surface a, parallel to surface b, with respect to connecting-rod c. Motor current J.

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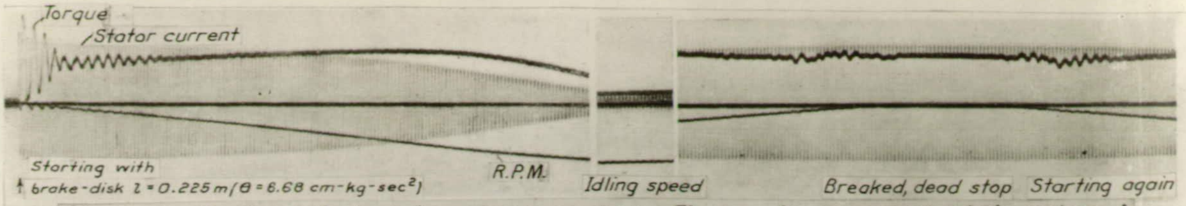

Fig. 14 Test with torsion dynamometer. Three-phase motor with rotor A

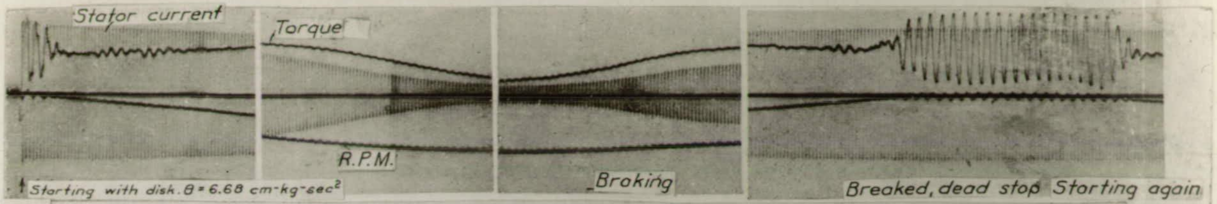

Fig. 15 Test with torsion dynamometer. Three-phase motor with rotor B

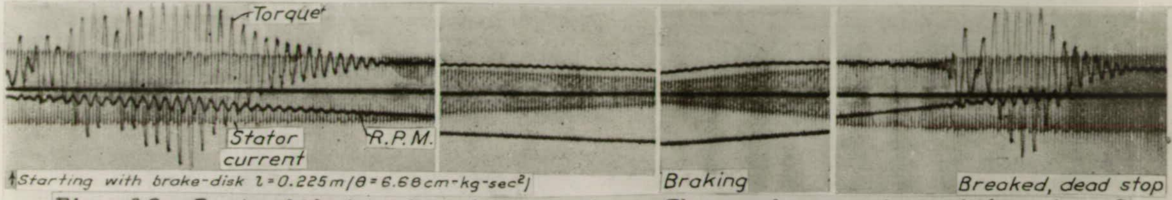

Fig. 16 Test with torsion dynamometer. Three-phase motor with rotor C

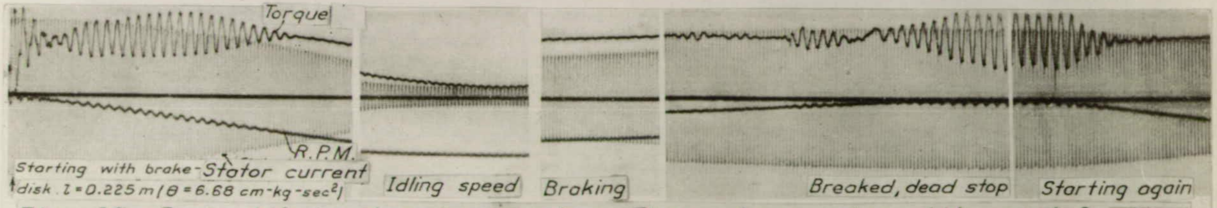

Fig. 17 Test with torsion dynamometer. Three-phase motor with special rotor

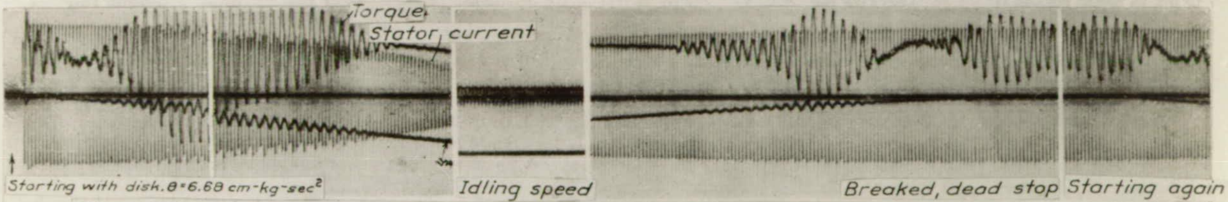

Fig. 18 Test with torsion dynamometer. Three-phase motor with rotor D

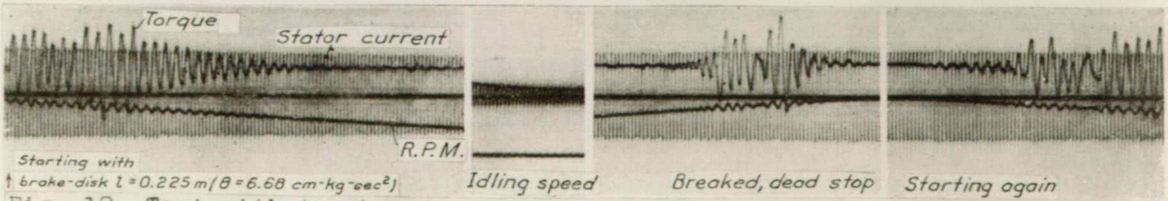

Fig. 19 Test with torsion dynamometer. Three-phase motor with eddy-current armature.

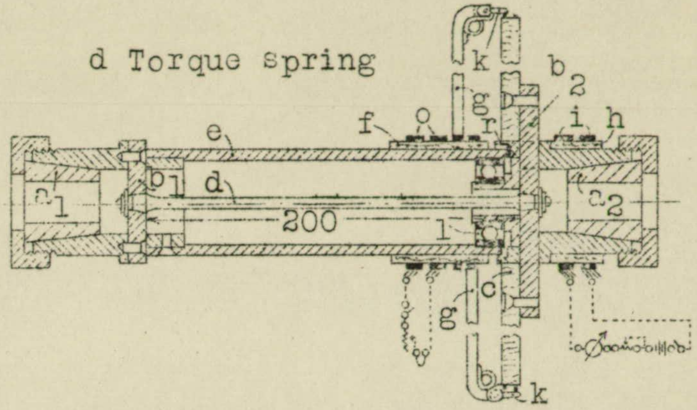
d Torque spring

Fig. 12 Torsion dynamometer

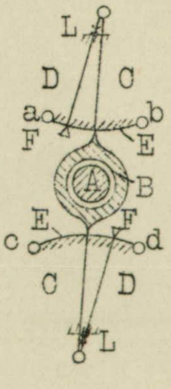

Fig. 20 Distortion gage with conversion