sults with the data obtained experimentally shows a satisfactory correlation.

Discussion and Conclusions

The method described previously seems to be a reliable and relatively simple one. It differs from the "capacity" or "condenser" methods used by other investigators for the same purpose [15–18]. The suggested method also differs basically from the principle described by I. O. MacConochie and A. Cameron [14] where the voltage drop across a film when a constant current (of 1 amp) is passed through the film was used for measuring the oil-film thickness.

It is the authors' opinion that the measurement of the film thickness should be done at the instant or just before the electrical breakdown occurs in the oil film causing an electrical discharge while the oil film is still in its "natural" condition. After an electrical breakdown in the film occurs and an electrical current starts passing through the film, the physical (and maybe also mechanical) properties of the liquid are considerably different from the natural oil-film properties existing under usual conditions. It is also possible that heat generated in an extremely small volume of liquid by the electrical current passing through this volume may evaporate a certain amount of liquid producing a two-phase lubricating film between the gear-teeth surfaces. The vapor generated between the surfaces may be a source of an additional pressure in the film, which can considerably change the total characteristics of the load carrying capacity of the lubricant.

The experiments indicate convincingly that, under certain operational conditions, there can be separation of mating gear teeth surfaces by a film of liquid lubricant. Under these conditions a pair of engaged spur gears run together and transmit the power without direct contact between them.

The experiments showed clearly the development of a hydrodynamic lubricating film between the gear teeth surfaces and established certain relationships between the load transmitted by the gearing and the minimum film thickness, for a given velocity of engagement and set of gears.

The separating film starts developing at a relatively low speed and its load carrying capacity increases with an increase in the velocity of engagement.

The relationship obtained between the minimum oil-film thickness and the transmitted load for given operating conditions is of the same order of magnitude as that predicted by theoretical analysis.

References

1 H. M. Martin, "The Lubrication of Gear Teeth," *Engineering*, vol. 102, 1916, p. 119.

2 E. K. Gatcombe, "Lubrication Characteristics of Involute Spur Gears," Trans. ASME, vol. 67, 1945, p. 177.

3 E. K. Gatcombe, "Non-Steady State Load-Supporting Capacity of Fluid Wedge-Shaped Films," Trans. ASME, vol. 73, 1951, pp. 1065–1075.

4 M. D. Hersey and D. B. Lowdenslager, "Film Thickness Between Gear Teeth," Trans. ASME, vol. 72, 1950, p. 1035.

5 E. T. Hutt, "Lubrication and Load-Carrying Capacity of Gears," *Lubrication Engineering*, vol. 8, no. 4, August, 1952, pp. 180–182.

6 A. Hundere, "Look at Problem of Gear Lubrication," *Lubrication Engineering*, vol. 15, no. 9, September, 1959, pp. 358–359.

7 J. F. Osterle, "Film Geometry Effects on Hydrodynamic Gear Lubrication," *Wear*, vol. 2, no. 6, 1959, pp. 461–432.

8 A. Petrusevich, "Fundamental Conclusions From the Contact Hydrodynamic Theory of Lubrication," *Izvestiya Akademii Nauk*, USSR, vol. 2, 1951, p. 209 (in Russian).

9 E. K. Gatcombe, "Physical Concepts of the Establishment of the Lubricating Oil Wedge and Its Associated Load Carrying Capacity for Mating Tooth Surfaces of High Speed Turbine Gear Equipment," Technical Publication No. 92, ASTM, Philadelphia, Pa., 1949, pp. 14–19.

10 D. W. Dareing and E. I. Radzimovsky, "Lubricating Film Thickness and Load Capacity of Spur Gears: Analytical Investigation" (submitted to ASME in December, 1961).

11 A. W. Crook, "The Lubrication of Rollers," *Philosophical Transactions*, series A, vol. 250, 1958.

12 A. W. Crook, "Some Studies of Wear and Lubrication," *Wear*, vol. 2, August, 1959, pp. 364–393.

13 El-Sisi and G. S. A. Shawki, "Measurement of Oil-Film Thickness Between Disks by Electrical Conductivity," Journal of Basic Engineering, Trans. ASME, Series D, vol. 82, 1960, pp. 8–12.

14 I. MacConochie and A. Cameron, "Measurement of Oil-Film Thickness on Gear Teeth," Journal of Basic Engineering, Trans. ASME, Series D, vol. 82, 1960, pp. 29–34.

15 E. F. Zommer, "Study on the Location of the Journal in a 120-Degree Fluid Friction Bearing at Constant and Alternating Loads" (in Russian). *Akadmiya Nauk*, USSR; *Friction and Wear in Machinery*, vol. 13, 1959, pp. 136–188.

16 W. Nücker, "Über den Schmiervorgang in Gleitlager," VDI Forschungsheft, 1932, Nr. 352.

17 A. Rumpf, "Reibung und Temperaturverlauf im Gleitlager," VDI Forschungsheft, 1938, Nr. 393.

18 D. S. Kodnir, M. D. Medvinskii, and E. F. Zommer, "A New Method and Instrumentation for the Study of Sliding Bearings," *Vestnik Mashinostroeniia*, 1955, no. 3 (in Russian).

19 E. I. Radzimovsky, "Power Losses and Efficiencies of Planetary Gear Drives," *Machine Design*, February 8, 1956, pp. 101–110.

20 E. I. Radzimovsky, "Planetary Gear Drives," *Machine Design*, June 11, 1959, pp. 144–153.

21 R. Kasuba, "Dynamic Loads on Spur Gear Teeth," thesis, Univ. of Illinois, Mech. Engrg. Dept. (unpublished).

DISCUSSION

M. D. Hersey[3]

The authors are to be congratulated for devising a new method of attack on the elusive problem of film thickness between gear teeth; and especially in obtaining test results of the same order as the values calculated in their analytical paper. The technique by which one of the test gears is held stationary seems promising.

Would it be possible to show in some detail how readings are made from an oscilloscope photograph like Fig. 9(d) before applying the calibration curve, Fig. 8? And how well do successive tests repeat? Is there any systematic difference, or hysteresis, in comparing observations with increasing and decreasing loads? In a method utilizing electrical breakdown we should anticipate so much scatter that a statistical treatment of the data might be required.

Can the friction power loss or mean coefficient of tooth friction be approximated from Table 1 in relation to speed, tooth load, and oil viscosity? What corrections are required for bearing friction?

Authors' Closure

We wish to thank Prof. M. D. Hersey for his comments and interest in our work on the measurement of film thickness between mating gear teeth.

With regard to the first question in the second paragraph, we want to mention that the type of oscilloscope signal shown in Fig. 9(d) was used primarily as an "indicator," and that no readings were taken from the signal itself. This type of signal indicated that the minimum film thickness between the mating gear teeth had reached a value during the period of engagement, which permitted electrical discharging to begin when the potentiometer was at a given setting. The operating conditions, torque on the output shaft, bulk temperature of the lubricant, and speed of the test gears in the equivalent gear train (1000 rpm), were recorded when the disturbance of the solid line in Fig. 9(c) was first noticed. These quantities were thus related to minimum film thickness by use of the calibration curve, Fig. 8.

The data shown in Table 1 were rechecked several times and the results from each test checked reasonably well. We feel that this measuring technique is consistent, as well as reliable, and that no statistical treatment of the data is necessary.

We do not believe that the power losses in the gear train can be determined from the data presented in this paper in Table 1. However, the testing machine described in this paper may be used for the accurate measurement of the efficiency of the gear

[3] Visiting Professor of Engineering (Research), Brown University, Providence, R. I. Fellow ASME.

drive and of an individual gear pair. A study of this kind was conducted recently by E. Radzimovsky, D. Offner, and R. Kasuba, and the results are prepared for publication. An attempt to predict the efficiency of a gear drive analytically and to check it experimentally using the machine described in this paper is the subject of a thesis being conducted at the present time by W. R. Adkins in the Department of Mechanical Engineering at the University of Illinois.

For a discussion of power loss and efficiencies of planetary gear drives, see references [19 and 20].