ΠΡΑΚΤΙΚΑ ΤΗΣ ΑΚΑΔΗΜΙΑΣ ΑΘΗΝΩΝ

ΣΥΝΕΔΡΙΑ ΤΗΣ 12ΗΣ ΔΕΚΕΜΒΡΙΟΥ 1974

ΠΡΟΕΔΡΙΑ ΔΙΟΝ. Α. ΖΑΚΥΘΗΝΟΥ

ΤΕΧΝΟΛΟΓΙΑ ΛΙΠΑΝΤΙΚΩΝ.— **Evaluation of Friction Modifiers in limited slip gear oils,** *by Andrew G. Papayannopoulos**. Ἀνεκοινώθη ὑπὸ τοῦ Ἀκαδημαϊκοῦ κ. Περ. Θεοχάρη.

What is a Friction Modifier.

A Friction Modifier is an additive with the ability to change the frictional profile of a lubricant in a machine. Frictional profile is the curve that shows how the coefficient of friction changes with sliding speed. A crude way of putting it is that friction modifiers lower the static coefficient of friction. Chemically, friction modifiers are long-straight chain, slender molecules with a polar group in the end. That group is supposed to give them affinity for the metal or other solid surfaces. The more active the polar group, the stronger the modifier is.

Here are some examples of friction modifiers:

$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2NH_2$

$(CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2O)_2P\text{-}OH$

$(CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2O)_2P{\lessgtr}^{O}_{OH}$

$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2COOH$

* ΑΝΔΡΕΟΥ Γ. ΠΑΠΑΓΙΑΝΝΟΠΟΥΛΟΥ, **Δοκιμασία τροποποιητῶν συντελεστοῦ τριβῆς εἰς λιπαντικὰ ἔλαια διὰ διαφορικὰ περιωρισμένης ὀλισθήσεως.**

Long chain amines, phosphites, phosphates, carboxylic acids, etc. Also salts or other derivatives of these materials possess friction modification properties.

How Friction Modifiers Work.

The mode of operation of a friction modifier is as follows :

When two lubricated solid surfaces slide against each other at low speeds and loads, a film of oil exists between them. The frictional for-

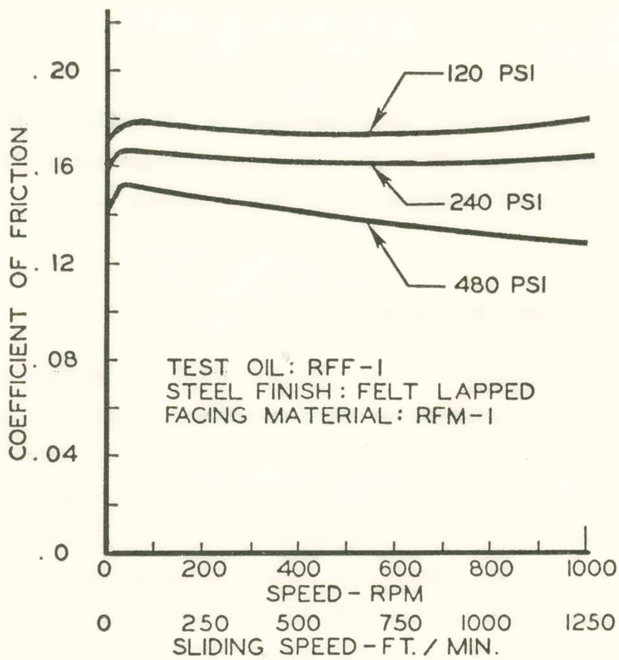

Fig. 1. Influence of interface unit pressure.

ces in this movement are controlled mainly by the viscosity and chemistry of that oil film. With a straight mineral oil, the static coefficient of friction is higher than the dynamic coefficient. If polar additives are added to that oil, they will tend to coat the two metal surfaces through adsorption or chemisorption. Now the two metal surfaces will rub against each other not only through the thin oil film but also through their coatings.

Therefore, the frictional forces will be different both under breakaway and dynamic conditions. How much different will depend on the type of polar additives, especially their molecular configuration. The long-straight chain polar materials, as the friction modifiers are, will tend to lay down upright on the metal surface as a closely packed for-

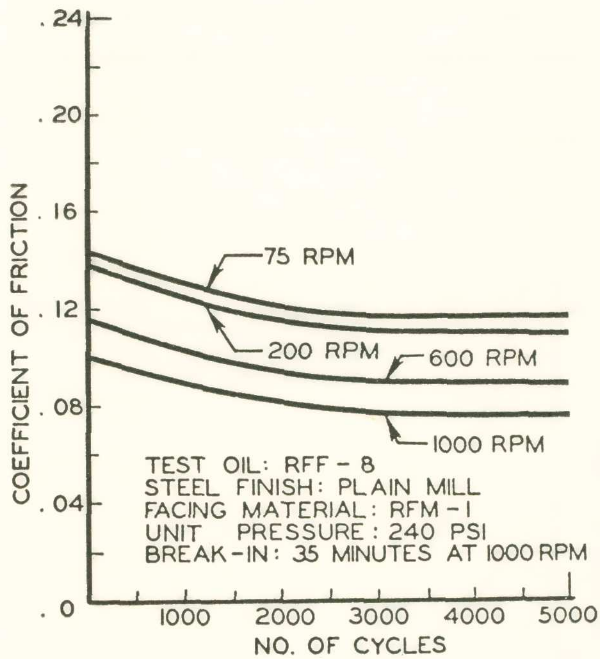

Fig. 2. Decreased friction with speed.

rest of molecules. It is like a carpet that covers many of the irregularities of the surfaces and makes sliding much easier. In other words, lowers the static coefficient. Fig. 3. The region where the friction modifiers for limited slip and other clutches operate can be described as one of low pressures, very low speeds and mostly boundary lubrication. Specifically, the pressures range from generally below 500 psi (0.35 Kg/mm^2) and the speeds from zero to a few RPM (or zero to 20 centimeters per second).

That means friction modification phenomena are observed at a region well below the one for antiwear or EP by at least an order of magnitude. Also, the running coefficients of friction of gears or other high speed and load machinery has no relation to the friction modification phenomena described above since they fall well outside that region.

Factors Affecting Frictional Properties.

The need and level of friction modification depends on the total system to be lubricated; and by system, we mean not only the mechanical parts and their configuration, but also the forces acting in it.

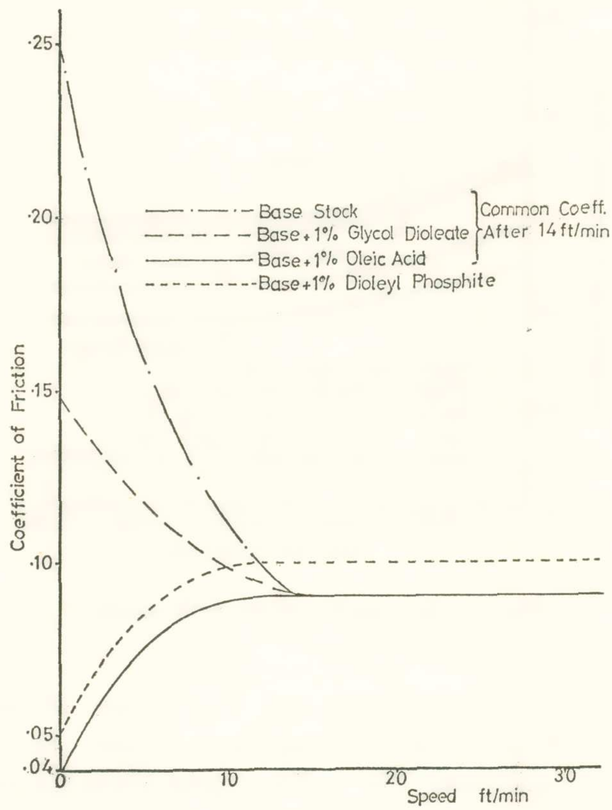

Fig. 3. Effect of Friction Modifiers on the Base Stock Friction - LVFA.

Bearing in mind the region of lubrication where these phenomena take place, here are some of the main factors involved:

1. Pressure.

Increasing the pressure lowers mainly the dynamic coefficient. See Fig. 1.

2. Speed.

Increased speed also lowers the whole frictional profile. See Fig. 2.

3. Facing Material.

Different facing materials exhibit different frictional profiles with the same lubricant. (Resin impregnated paper, asbestos, graphite containing matrixes, sintered bronze, even steel).

4. Temperature.

The higher the temperature, the lower the static coefficient of friction and usually the dynamic also.

5. Chemical Composition.

The effect of chemistry on the frictional profile is indeed great. Through the use of friction modifiers, a formulator can give his lubricant the desired frictional profile.

6. Oil Degradation.

Degradation of the fluid mainly through oxidation can change the frictional profile. Oxidation destroys the friction modifier and also creates new and unsatisfactory polar molecules. To insure friction durability, the formulator will chose not only stable additives, but also will include antioxidants in his formula.

Friction modifiers find application in many types of lubricants. Here are some examples:

— Automatic transmission fluids (ATF) for GM (Dexron, Chrysler MS - 4228) to prevent squawk.
— Limited Slip gear oils to prevent chatter.
— Way lubricants (for slideways) to prevent stick-slip.
— Tractor wet brake oils to prevent chatter.

On these applications, the present discussion will deal with the Limited Slip gear oils.

Brief Description of a Limited - Slip Differential.

A standard differential (Fig. 4) transmits equal torque to each axle shaft. The limited-slip differential (Fig. 5) allows unequal amounts of torque (torque biasing) to be transmitted to each axle shaft. Thus, the wheel on a high traction surface can develop a high torque and help to move the vehicle when the other wheel is on a low traction surface (Fig. 6). This is very useful when one wheel drives over ice or sand or a slippery surface.

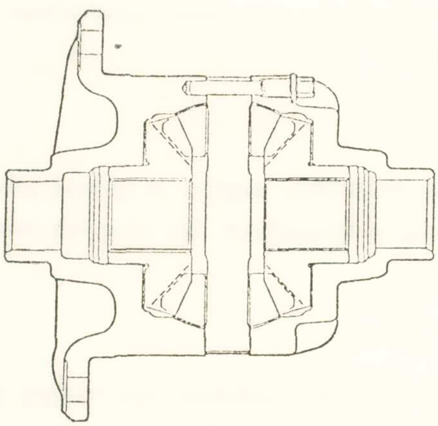

Fig. 4. Standard Differential.

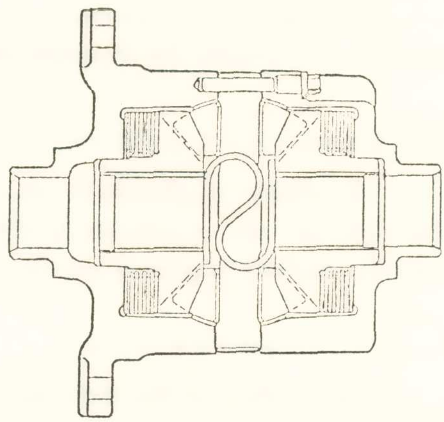

Fig. 5. Limited - Slip Differential.

The performance of a limited-slip differential-oil system is evaluated by the degree it can transmit unequal power (bias ratio) and by the absence of audible noise (chatter). Bias ratio is the ratio of the torque on the high torque wheel (on better traction surface) to the torque on the slipping wheel. Thus, the bias ratio is a measurement of how effective the differential assembly is in improving the traction capacity of the vehicle. A moderately high bias ratio is desirable. Too high a ratio would make the unit resist differentiation and lock-up when making a turn.

The most popular form of limited-slip differential uses clutch plates which are attached to the carrier (driving plates) and each axle shaft (driven ones). As these clutch plates turn and rub against each other (the driving against the driven ones) during a turn, they could stick and slip noisily in the presence of a bad friction modifier or slide smoothly and quietly in the presence of a good one.

Testing for the bias ratio is relatively easy. With one wheel of the car on a slippery surface, the car is driven over a 2×4 board. If the car succeeds to go over the board, the bias ratio is considered satisfactory.

Testing, however, the friction modifiers for chatter control is a very costly and time consuming operation. The tests used employ one or more cars equipped with critical limited-slip axles.

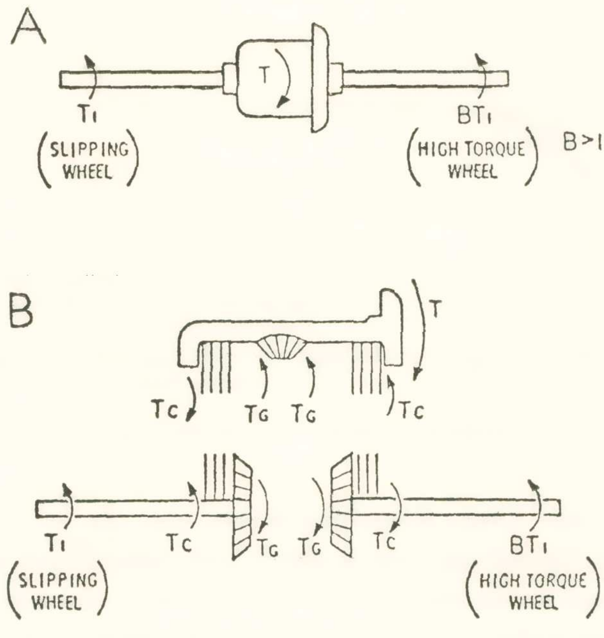

Fig. 6. Torque Diagrams: A-external
B-internal.

The evaluation is divided into two parts, the initial performance and the durability, or long-term performance. The testing for the initial limited-slip properties (or frictional properties) of limited-slip gear oils involves one or more critical limited-slip cars. These cars are driven in tight turns or figure eight turns, very slowly, and any noise (chatter) or other vibration from the axle is noted. Any such noise denotes stick-slip phenomena, i.e., failure of the friction modifier to provide a lower static than the dynamic coefficient of friction. The testing for the long-term frictional properties or durability of the friction modifier is more involved. The best way is through a field test using 10 - 20 cars equipped with limited-slip axle and each one driven for 50,000 miles or more. If no appreciable chatter is experienced, the friction modifier is termed successful. Another way is through an accelerated oil deterioration pro-

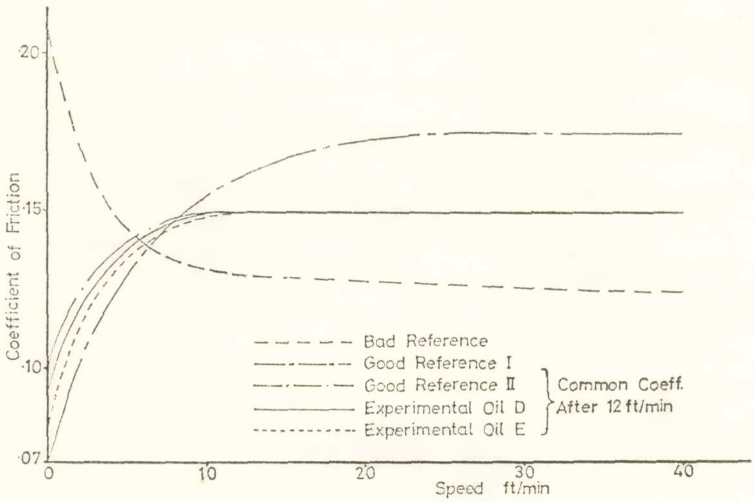

Fig. 7. LVFA Frictional Profiles of Limited-Slip Gear Oils (New).

cedure called the Little Wheel/Big Wheel test. In it, a car equipped with a critical limited-slip axle is fitted with unequal size tires and driven on the road or on chassis rolls. In this way the axle is forced to constantly differentiate and thus deplete the friction modifier and in general, deteriorate the oil. In this test, 1000 miles is roughly equivalent to 10,000 miles of regular operation.

Research on a Simpler Test.

Considerable work has been carried out throughout the industry for a simpler way to evaluate friction modifiers in limited-slip gear oils. Unfortunately, most of this work has been unsuccessful. This paper, however, is presenting a new method for a quick, simple and inexpensive evaluation of friction modifiers in these oils.

The method uses the Low Viscosity Friction Apparatus (LVFA). This apparatus is based on a 1-3/16 in. mean diameter, 1/16 in. wide frictional material annulus rotating against a flat steel surface. Friction

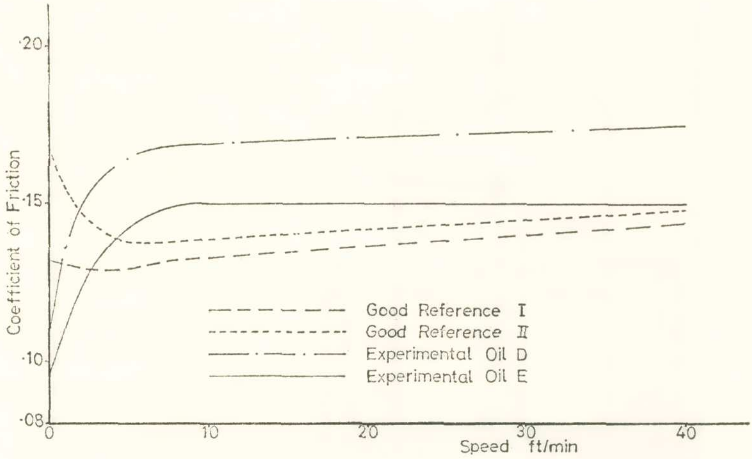

Fig. 8. LVFA Frictional Profiles of Aged Limited-Slip Gear Oils.

is measured as a function of sliding speed and plotted on a XY recorder, giving frictional profiles like the ones in Fig. 3. A schematic diagram is given in Fig. 9 and a test procedure in Appendix I.

For an evaluation of the initial frictional properties of a limited-slip gear oil, the test is run on a sample of new oil. To measure the durability of a friction modifier in a limited-slip gear oil, the sample is first aged in the lab. The aging is accomplished by submitting the oil to the Beaker Oven test at chosen temperatures and periods of time. For example, 300^0 F and 48 or 72 hours. The Beaker Oven test utilizes a 250 cc glass beaker in which 100 cc of oil sample is poured. Then, a steel strip of 7 cm $\times$ 1.5 cm $\times$ 2 mm made of SAE 1010 steel is inserted into the beaker and immersed, at an angle, in the oil. The beaker-oil-strip assembly is placed in a constant temperature oven for aging for the specified period of time. During the Beaker Oven test, the oil and the friction modifier in it is constantly subjected to the degrading forces of thermal energy and oxidation as well as the catalytic effect of Iron. At the end of the test, a sample of the aged oil is tested again in the LVFA for frictional properties. If the frictional profile has been altered to the extent that the static coefficient of friction is now bigger than the dynamic coefficient, the oil at this level of deterioration would be expected to chatter in a limited-slip axle.

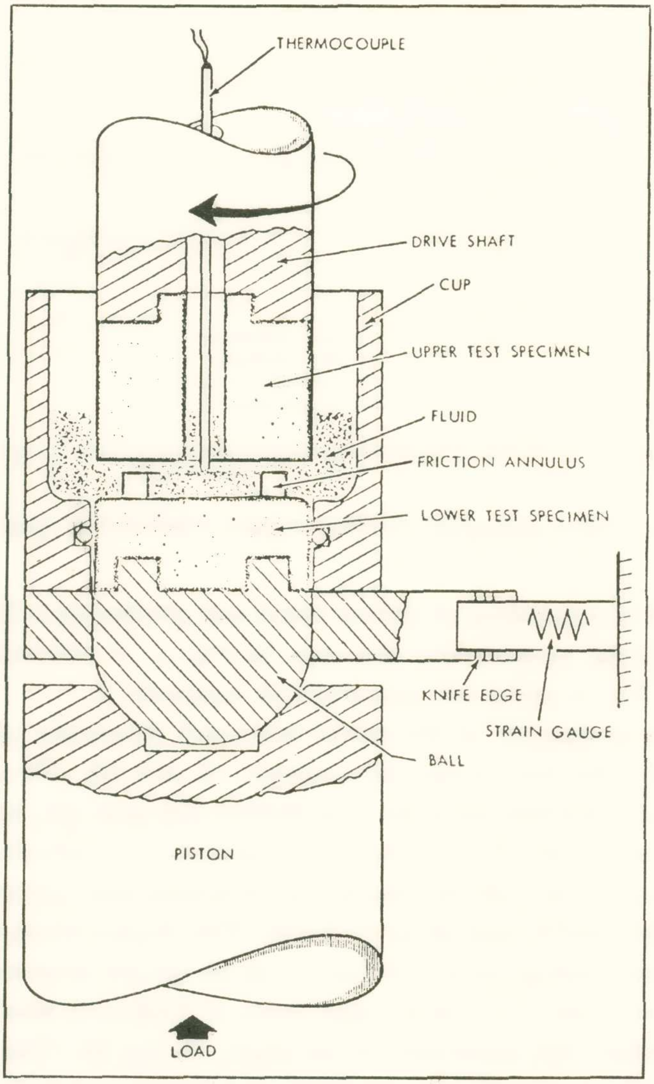

Fig. 9. Low Velocity Friction Apparatus.

The above proposed method for evaluating friction modifiers in limited-slip gear oils correlates well with the full scale car test, i.e., the Little Wheel/Big Wheel test (LW/BW) and Fig. 7 shows the frictional profiles of several limited-slip gear oils, when new, in the LVFA. With the exception of the bad reference (as expected) both good reference oils and two experimental gear oils give good frictional profiles.

These ratings by the LVFA are totally confirmed by the Little Wheel/Big Wheel car test as shown in Table I.

After aging in the lab, the same oils were subjected to the LVFA test. The results, shown in Fig. 8, indicate that drastic changes occurred in the frictional profile of two reference oils. Those changes would be translated into chatter in the Little Wheel/Big Wheel car test at that stage of oil degradation. This prediction was again confirmed by the actual Little Wheel/Big Wheel test as shown in Table II. The oils that did not change their profile in the LVFA after aging fared better in this car test. Interestingly, two experimental oils fared better than the good reference oils in both tests.

Thus, from Tables I and II, it is evident that the test oils were rated in the same order by both the LVFA bench test and the LW/BW test which is a full scale test, and in a condensed way, a fleet test. This proves the good correlation of the proposed bench test and the full scale limited-slip test.

In a further effort to establish the final proof of the ability of the bench test to predict field performance, three of the above oils were tested in two fleet tests. The oils were Bad Reference, Good Reference II and Experimental Oil D. The test cars were ten 1972 Chevrolet Station Wagons (V-8 engine, Automatic Transmission) and ten 1972 Ford 4-Door Sedans (V-8 engine, Automatic Transmission).

The Bad Reference started chattering immediately in the Chevrolets, and in less than 100 miles in the Fords. The Good Reference II started chattering after 5,000 to 10,000 miles in the Chevrolets, and after 15,000 to 20,000 miles in the Fords. The Experimental Oil D is continuing to give chatter-free performance in all cars even after 50,000 to 80,000 miles of operation in each one.

CONCLUSIONS

A simple, quick and inexpensive test method has been developed for the evaluation of friction modifiers for limited-slip gear oils. This method correlates well with full scale or field tests and it can be of help in the development of new and improved-slip gear oils.

TABLE I

Evaluation of Frictional Properties of Limited-Slip Gear Oils (New) through both LVFA and LW/BW Tests.

Oil	Chatter in LW/BW Test	LVFA Rating
Good Reference I	None	Good
Good Reference II	None	Good
Bad Reference	Medium	Bad
Experimental Oil D	None	Good
Experimental Oil E	None	Good

TABLE II

Evaluation of Friction Durability of Limited-Slip Gear Oils through both LVFA (Aged Oils) and LW/BW Tests.

Oil	Chatter in LW/BW Test After Miles	LVFA Rating (Aged Oils)
Good Reference I	3,000	Fair
Good Reference II	800	Bad
Experimental Oil D	8,000 +	Good
Experimental Oil E	6,250 +	Good

APPENDIX I

LVFA PROCEDURE

Both lower and upper test specimens are cleaned with n-pentane and subsequently with isopropyl alcohol and dried. After they are positioned in the apparatus, the test oil (12 ml.) is added into the cup and the two specimens are brought into the contacting position. Pressure is applied to the lower specimen (120 psi or 0.083 Kg/mm^2) through an air floated piston. Rotation is started very, very slowly, and carefully in order to obtain an accurate measurement of the static coefficient of friction and its transition into dynamic. Then, the speed is gradually increased until it reaches 40 ft./min. (20 cm./sec.) when the apparatus is stopped. The frictional force between the rubbing surfaces is measured using a strain gauge and it is plotted on an XY recorder vs. sliding speed.

ΠΕΡΙΛΗΨΙΣ

Τροποποιηταὶ τοῦ συντελεστοῦ τριβῆς λιπαντικῶν εἶναι χημικαὶ οὐσίαι, ἀποτελούμεναι ἀπὸ μόρια μὲ μακρὰν εὐθεῖαν ἄλυσον ἀνθράκων καὶ μίαν πολικὴν ὁμάδα εἰς τὸ ἄκρον.

Δι᾽ ἐπιρροφήσεως ἐπὶ μεταλλικῶν καὶ ἄλλων στερεῶν ἐπιφανειῶν, προκαλοῦν τὴν μείωσιν τοῦ στατικοῦ συντελεστοῦ τριβῆς καὶ οὕτως ἐπιτρέπουν τὴν ὁμαλὴν ὀλίσθησίν των πρὸς ἀλλήλας, ἄνευ τοῦ φαινομένου «κόλλησις - ὀλίσθησις» (stick - slip). Τὸ φαινόμενον τοῦτο προκαλεῖ τὸν γνωστὸν ἐνοχλητικὸν θόρυβον (chatter) εἰς διαφορικὰ περιωρισμένης ὀλισθήσεως, ὅταν τὸ λιπαντικόν των δὲν περιέχῃ ἢ ἔχῃ ἀπολέσει τοὺς πρώην προστεθέντας τροποποιητὰς τριβῆς.

Ἡ ἀνάπτυξις καταλλήλων λιπαντικῶν, διὰ διαφορικὰ περιωρισμένης ὀλισθήσεως, βασίζεται εἰς τὴν ἐξεύρεσιν καταλλήλων τροποποιητῶν τοῦ συντελεστοῦ τριβῆς, οἱ ὁποῖοι διατηροῦν τὰς ἰδιότητάς των καὶ κατόπιν μακρᾶς λειτουργίας.

Ἡ δοκιμασία τῶν τροποποιητῶν τοῦ συντελεστοῦ τριβῆς, εἰς λιπαντικὰ διαφορικῶν περιωρισμένης ὀλισθήσεως, εἶναι δυσχερής, μακρά, καὶ δαπανηρά, χρησιμοποιοῦσα ἓν ἢ περισσότερα ὀχήματα ἐπὶ μακρὸν χρόνον. Πολυάριθμοι ἐργαστηριακαὶ δοκιμασίαι ἔχουν ἀποδειχθῆ ἀπογοητευτικαί, διότι δὲν συσχετίζονται πρὸς τὴν πραγματικότητα.

Εἰς τὴν παροῦσαν ἐργασίαν ἐφηρμόσθη μία νέα μέθοδος, ἡ ὁποία ἀπεδείχθη λίαν ἀποτελεσματικὴ εἰς τὴν δοκιμασίαν καὶ τὴν ἐκλογὴν τροποποιητῶν συντελεστοῦ τριβῆς, ὡς καὶ τῶν ἀντιστοίχων λιπαντικῶν.

Ἡ μέθοδος αὕτη χρησιμοποιεῖ τὴν Συσκευὴν Τριβῆς Χαμηλῶν Ταχυτήτων, ἐν συνδυασμῷ πρὸς χημικὰς δοκιμασίας διὰ τεχνητὴν παλαίωσιν λιπαντικῶν.

Ἡ συσκευὴ δίδει τὰ ἀποτελέσματα, ὑπὸ μορφὴν διαγραμμάτων, τοῦ συντελεστοῦ τριβῆς συναρτήσει τῆς ταχύτητος ὀλισθήσεως. Τὸ προφὶλ τοῦτο τῆς μεταβολῆς τοῦ συντελεστοῦ τριβῆς ἀποκαλύπτει τὴν ἱκανότητα τοῦ λιπαντελαίου νὰ ἀποκλείῃ τὴν ἐμφάνισιν τοῦ φαινομένου «κόλλησις - ὀλίσθησις».

Οὕτως, ἓν ἐπιθυμητὸν προφὶλ ἀρχίζει ἀπὸ σχετικῶς μικρὸν ὕψος (χαμηλὸς στατικὸς συντελεστὴς τριβῆς) καὶ προχωρεῖ εἰς μεγαλύτερον ὕψος, καθὼς ἡ ταχύτης ὀλισθήσεως αὐξάνει (ὑψηλὸς κινητικὸς συντελεστής). Ἀντιθέτως, ἓν ἀκατάλληλον λιπαντέλαιον παρέχει προφίλ, ὅπου ὁ στατικὸς συντελεστὴς εἶναι ὑψηλότερος τοῦ κινητικοῦ.

Τὸ σχῆμα καὶ τὸ ὕψος τοῦ προφὶλ τοῦ συντελεστοῦ τριβῆς εἶναι συνάρτησις — πλὴν τῶν χημικῶν οὐσιῶν τοῦ λιπαντελαίου — τῆς πιέσεως, ταχύτητος, θερμοκρασίας, συστάσεως καὶ ἐπιφανειακῆς ἐμφανίσεως τῶν δοκιμίων τριβῆς.

Τροποποιηταὶ τριβῆς, οἱ ὁποῖοι ἀπεδείχθησαν ἱκανοποιητικοί, κατὰ τὰς δοκιμασίας εἰς τὴν συσκευὴν ταύτην, περιλαμβάνουν πρωτοταγεῖς, δευτεροταγεῖς ἢ τριτοταγεῖς ἀμίνας μὲ ἁλύσους δέκα ὀκτὼ ἀνθράκων ἑκάστη, καρβοξυλικὰ ὀξέα τύπου ἐλαϊκοῦ καὶ στεαρικοῦ, καὶ ὀξίνους φωσφορικοὺς ἐστέρας μὲ ὁμοίας μακρὰς καὶ εὐθείας ἁλύσους. Ἐπίσης, ἅλατα τῶν ἀνωτέρω οὐσιῶν εὑρέθησαν νὰ ἔχουν ὁμοίας ἰδιότητας τροποποιητοῦ τριβῆς.

Ἡ μακρὰ χρῆσις τοῦ ἐλαίου (δι᾽ ὀξειδώσεως καὶ θερμικῆς διασπάσεως) δύναται νὰ μετατρέψῃ ἓν καλὸν προφὶλ εἰς ἀκατάλληλον. Ἐργαστηριακῶς ἐπιτυγχάνεται τὸ αὐτὸ ἀποτέλεσμα διὰ τεχνητῆς παλαιώσεως τοῦ ἐλαίου. Τοιουτοτρόπως, δύναται νὰ μετρηθῇ ἡ χρήσιμος ζωὴ ἑνὸς ἐλαίου καὶ νὰ ἀναπτυχθοῦν βελτιωμένα προϊόντα.

Ἡ ὡς εἴρηται μέθοδος ἐπιτρέπει τὴν δοκιμασίαν μεγάλου ἀριθμοῦ χημικῶν οὐσιῶν, ὄχι μόνον δι᾽ ἀρχικῶς καλὸν προφὶλ τριβῆς, ἀλλὰ καὶ διὰ τὴν ἱκανότητα ἐπιβιώσεως ὑπὸ συνθήκας ὀξειδώσεως καὶ θερμικῆς διασπάσεως.

Τὰ πειραματικὰ ἀποτελέσματα, ἅτινα ἐλήφθησαν μὲ τὴν νέαν μέθοδον, εὑρέθησαν νὰ συμφωνοῦν πρὸς τὰ ἀποτελέσματα, ληφθέντα δι᾽ ὀχημάτων ἐξωπλισμένων μὲ διαφορικὰ περιωρισμένης ὀλισθήσεως.

Παραδείγματα συσχετίσεως δεικνύουν ὅτι παλαίωσις 72 ὡρῶν εἰς τὸ ἐργαστήριον ἰσοδυναμεῖ μὲ παλαίωσιν ἐλαίου ληφθέντος :

1. Κατόπιν περίπου 3.000 μιλλίων δι᾽ αὐτοκινήτου ἐξωπλισμένου μὲ ὀπισθίους τροχοὺς ἀνίσου μεγέθους, ἢ

2. Κατόπιν περίπου 30.000 μιλλίων ὁμαλῆς λειτουργίας τοῦ αὐτοκινήτου μὲ τροχοὺς κανονικοῦ μεγέθους.

Διὰ τῆς ἀνωτέρω προτεινομένης μεθόδου βοηθεῖται σημαντικῶς ἡ ἔρευνα διὰ νέους καὶ καλυτέρους τροποποιητὰς συντελεστοῦ τριβῆς καί, συνεπῶς, ἡ ἀνάπτυξις καὶ ὁ σχεδιασμὸς βελτιωμένων λιπαντικῶν διὰ διαφορικὰ περιωρισμένης ὀλισθήσεως.

REFERENCES

1. G. R. Smith, V. J. Jandasek, S. R. Sprague and R. B. Singer, A New Concept of Measuring Frictional Characteristics, Summer SAE Meeting, 1961.

2. N. A. Nann and F. H. Pinchbeck, Tailoring Automatic Transmission Fluid Shift Quality in the Laboratory, May SAE Meeting, 1965.
3. M. L. Haviland, J. J. Rodgers and E. D. Davison, Surface Temperatures and Friction in Lubricated Clutches, January SAE Meeting, 1963.
4. G. J. Liddell and T. D. Newingham, Some Physical Effects of Transmission Fluid Degradation, January SAE Meeting, 1966.
5. Development of Research Techniques for Determining Friction Characteristics of Automatic Transmission Fluids, CRC Report No. 377, March 1964.
6. ASLE Lubrication Fundamentals Committee 1972. Friction and Wear Devices, 36, 118, 140, 261.
7. R. H. Haas and R. C. Manwaring, Development of a Limited Slip Differential, June SAE Meeting, Montreal, Canada, 1971.
8. A. G. Papay and P. N. Slimming, Evaluation of Friction Modifiers, Institute of Petroleum Sumposium, April 1973.

*

Λαβὼν τὸν λόγον ὁ Ἀκαδημαϊκὸς κ. **Περ. Θεοχάρης,** εἶπε τὰ ἑξῆς:

Ἔχω τὴν τιμὴν νὰ παρουσιάσω εἰς τὴν Ἀκαδημίαν ἐργασίαν τοῦ κ. Ἀνδρέου Γ. Παπαγιαννοπούλου, διδάκτορος τοῦ Ε. Μ. Πολυτεχνείου. Ὁ κ. Παπαγιαννόπουλος εἶναι ἀπόφοιτος τοῦ Ἐθνικοῦ καὶ Καποδιστριακοῦ Πανεπιστημίου Ἀθηνῶν, ἀποφοιτήσας ἐκ τοῦ τμήματος Χημείας τῆς Φυσικομαθηματικῆς Σχολῆς του, κατὰ τὸ ἔτος 1951.

Ἐν συνεχείᾳ οὗτος εἰσῆλθεν εἰς τὸ Colorado School of Mines τῶν Η.Π.Α. καὶ εἰς τὸ τμῆμα Petroleum Refining Engineering, ἔνθα ἐξεπόνησε διατριβὴν μὲ τίτλον: «A New Column for Liquid Thermal Diffusion» καὶ ἀνηγορεύθη Master of Science in Petroleum Refining Engineering κατὰ τὸ ἔτος 1959.

Μετὰ τὰς ἐν Η.Π.Α. σπουδάς του εἰργάσθη τόσον εἰς τὴν Βιομηχανίαν Πετρελαίου, ὅσον καὶ εἰς Πανεπιστήμια τῶν Η. Π. Α. μέχρι σήμερον, ἐξεπόνησε δὲ σειρὰν πρωτοτύπων ἐργασιῶν, δημοσιευθεισῶν εἰς ἔγκυρα ἐπιστημονικὰ περιοδικά, καθὼς καὶ διπλωμάτων εὑρεσιτεχνίας.

Κατὰ τὸ ἔτος 1974 ἀνηγορεύθη διδάκτωρ τοῦ Ε. Μ. Πολυτεχνείου ἐκ τῆς Σχολῆς Χημικῶν Μηχανικῶν, ἐκπονήσας διατριβὴν μὲ θέμα: «Συμβολὴ εἰς τὸν σχεδιασμὸν λιπαντικῶν ἐλαίων ὑψηλῆς πιέσεως (Υ. Π.) τύπου Θείου καὶ Φωσφόρου δι' ὀδοντωτοὺς τροχούς».

Ἡ ἐπιστημονικὴ ἐργασία τοῦ κ. Παπαγιαννοπούλου, τὴν ὁποίαν ἔχω τὴν τιμὴν νὰ παρουσιάσω σήμερον ἐνταῦθα, ἔχει τὸν τίτλον: «Δοκιμασία τροποποιητῶν συντελεστοῦ τριβῆς εἰς λιπαντικὰ ἔλαια διὰ διαφορικὰ περιωρισμένης ὀλισθήσεως».

Οἱ τροποποιηταὶ συντελεστοῦ τριβῆς λιπαντικῶν εἶναι χημικαὶ οὐσίαι, ἀποτελούμεναι ἀπὸ μακρομόρια, ἔχοντα μακρὰν εὐθεῖαν ἅλυσον ἀνθράκων, καὶ πολικὴν ὁμάδα εἰς τὸ ἄκρον.

Δι' ἐπιρροφήσεως τῶν οὐσιῶν τούτων ἐπὶ μεταλλικῶν ἢ ἄλλων στερεῶν ἐπιφανειῶν προκαλοῦν αὗται τὴν μείωσιν τοῦ στατικοῦ συντελεστοῦ τριβῆς καὶ οὕτως ἐπιτρέπουν τὴν ὁμαλὴν ὀλίσθησιν τῶν ἐπιφανειῶν πρὸς ἀλλήλας ἄνευ τοῦ φαινομένου τῆς «κολλώδους ὀλισθήσεως» (stick - slip).

Τὸ φαινόμενον τοῦτο προκαλεῖ τὸν γνωστὸν ἐνοχλητικὸν θόρυβον (chatter) εἰς τὰ διαφορικὰ μηχανῶν ἐσωτερικῆς καύσεως περιωρισμένης ὀλισθήσεως, ὅταν τὸ λιπαντικόν τους δὲν περιέχῃ ἢ ἔχῃ ἀπολέσει τοὺς πρώην προστεθέντας τροποποιητὰς τριβῆς. Ἡ ἀνάπτυξις καταλλήλων λιπαντικῶν διὰ διαφορικὰ περιωρισμένης ὀλισθήσεως βασίζεται εἰς τὴν ἐξεύρεσιν καταλλήλων τροποποιητῶν τοῦ συντελεστοῦ τριβῆς, οἱ ὁποῖοι διατηροῦν τὰς ἰδιότητάς των καὶ μετὰ μακρὰν λειτουργίαν τῆς μηχανῆς.

Ἡ δοκιμασία τῶν τροποποιητῶν τοῦ συντελεστοῦ τριβῆς εἰς λιπαντικὰ διαφορικῶν περιωρισμένης ὀλισθήσεως εἶναι δυσχερής, μακρὰ καὶ δαπανηρά, χρησιμοποιοῦσα ἓν ἢ περισσότερα ὀχήματα καὶ ἐπὶ μακρὸν χρόνον. Πολυάριθμοι ἐργαστηριακαὶ δοκιμασίαι ἀπεδείχθησαν ἤδη ἀνίκανοι, ὡς μὴ συσχετιζόμεναι πρὸς τὴν πραγματικότητα.

Εἰς τὴν παροῦσαν ἐργασίαν ἐφηρμόσθη νέα μέθοδος, ἡ ὁποία ἀπεδείχθη ἀποτελεσματικὴ διὰ τὴν δοκιμασίαν καὶ τὴν ἐκλογὴν τῶν καταλλήλων τροποποιητῶν τοῦ συντελεστοῦ τριβῆς, ὡς καὶ τῶν ἀντιστοίχων λιπαντικῶν. Ἡ μέθοδος αὕτη χρησιμοποιεῖ τὴν συσκευὴν μελέτης τῆς τριβῆς χαμηλῶν ταχυτήτων ἐν συνδυασμῷ πρὸς τὰς ἀντιστοίχους χημικὰς δοκιμασίας διὰ τὴν τεχνητὴν παλαίωσιν λιπαντικῶν.

Πειραματικὰ ἀποτελέσματα, ληφθέντα διὰ τῆς νέας μεθόδου, συμφωνοῦν πρὸς τὰ ληφθέντα ἀποτελέσματα δι' ὀχημάτων ἐξωπλισμένων μὲ διαφορικὰ περιωρισμένης ὀλισθήσεως.

Διὰ τῆς ἀνωτέρω προτεινομένης μεθόδου ὑποβοηθεῖται σημαντικῶς ἡ ἔρευνα διὰ τὸν ἔλεγχον νέων καὶ καλυτέρων τροποποιητῶν τοῦ συντελεστοῦ τριβῆς καί, συνεπῶς, ἡ ἀνάπτυξις καὶ ὁ σχεδιασμὸς βελτιωμένων λιπαντικῶν διὰ διαφορικὰ περιωρισμένης ὀλισθήσεως.

Διὰ περισσοτέρας πληροφορίας παραπέμπω τοὺς ἐνδιαφερομένους εἰς τὰ Πρακτικὰ τῆς Ἀκαδημίας.