Development of Exclusive Fluid for AWD Coupling^{*1}

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This paper describes the analysis of the shudder generation mechanism in AWD couplings and the development of a special Toyoda ITCC Fluid "TIF" enabling an Intelligent Torque Controlled Coupling ("ITCC") with larger capacity that is applicable to large-size vehicles and that achieves better fuel efficiency due to size and weight reduction of the rear drivetrain. Optimization of the additives and base oil of this fluid, which is exclusive for AWD couplings, has improved anti-shudder durability, reduced maximum torque at low temperatures, and achieved both reliability improvement and weight reduction of the driveline.

Key Words: AWD coupling, fluid, additives, metallic detergent, EP-agent, dispersant, FM, synthetic fluid, shudder

1. Introduction

Recently in the automobile drivetrain component industry, more emphasis has been placed on the development of products that can help achieve higher capacity and better fuel efficiency on top of improved vehicle safety and operability. There have also been demands for JTEKT's electronically controlled coupling ITCC¹⁾ (Intelligent Torque Controlled Coupling) for AWD vehicles to be further improved in the areas of service life, compactness, and capacity and for the peak torque to be reduced in order to achieve weight reduction of the rear drivetrain which contributes to better fuel economy.

ITCC is a power transmission device which enables instantaneous distribution of optimum torque through electronic control to the rear and front wheels in accordance with vehicle running conditions and road surface conditions. The structure of the ITCC, as illustrated in Fig. 1, is composed of a paper-based wet type multi-disc clutch and an iron-based electromagnetic clutch, both of which are lubricated by a common fluid. For extension of ITCC service life, it is critical to prevent self-excited vibration called shudder²⁾, which is influenced to a great extent by the anti-shudder property of the lubrication fluid therein. Shudder is generated at the sliding surface of the clutch due to stick slip. It has been known that for this stick slip on the sliding surface to take place, a necessary condition is that the dependency of the coefficient of friction (μ) on the velocity (v) (μ -v characteristics) must have a negative slope $(d\mu/dv < 0)^{3}$. Therefore, a positive slope for the coefficient of friction

against velocity $(d\mu/dv \ge 0)$ is effective to prevent shudder from occurring⁴⁾⁻⁷⁾. On the other hand, for the sake of making the rear drivetrain lightweight, it is effective to stabilize the peak torque of ITCC throughout the whole temperature range. Particularly in the low temperature range, as the viscous fluid resistance between the clutches becomes predominant, viscosity of the fluid becomes influential.

In such backdrops, while the ATF (Automatic Transmission Fluid) has traditionally been used as the ITCC lubrication fluid, it has become necessary to develop a new fluid dedicated for ITCC in order to satisfy the above-mentioned requirements. This paper presents an analysis of the shudder generation as well as development of an exclusive ITCC fluid (TIF: Toyoda ITCC Fluid) which has made possible a landmark improvement of ITCC performance.



Fig. 1 Structure of ITCC

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2. Methods of Experiment and Analysis

2. 1 Shudder Test on Actual Coupling Unit

Using an actual ITCC unit as shown in **Fig. 1**, various fluids were subjected to an anti-shudder durability test. While keeping the loading power at 350 W and the oil temperature at 140°C, a continuous clutch slip test was conducted during which the chronological change of the μ -v slope was monitored. The time from test start until the μ -v slope became 1 or below (shudder generation) was determined as the anti-shudder life.

2. 2 Shudder Test on Paper Wet Clutch Proper

Using a paper wet type clutch proper in compliance with the JASO M349-2001 standard⁸⁾, the anti-shudder life of various fluids was evaluated on the LVFA (Low Velocity Friction Apparatus) tester with the fluid temperature kept at 140° C.

2. 3 Analysis of Fluid

The change of the additive composition of the fluid accompanying the shudder test was analyzed by use of a Fourier transform infrared spectrophotometer (FT-IR), wherein the remnant of the main elements was quantitatively analyzed based on inductively coupled plasma emission spectrometry (ICP).

3. Improvement of Anti-Shudder Life by Optimization of Additives

3. 1 Mechanism of Fluid Degeneration

Figure 2 shows the chronological change of the μ -v slope resulting from a test of commercialized ATF on the actual coupling durability test. The vertical axis represents the value obtained by dividing the coefficient of friction at the sliding velocity of 0.23 m/s by that at the sliding velocity of 0.009 m/s. Basically, if this μ -v slope is 1 or greater, the coefficient of friction is supposed to have positive velocity-dependence, suggesting excellent anti-shudder capability. From **Fig. 2**, the commercialized ATF showed a decline of the μ -v slope with an increase of test time until shudder took place.

Here, in an effort to clarify the factors that contributed to generation of shudder in this form of test, we checked the extent to which the μ -v slope could be recovered by replacing the used fluid in the shuddering coupling with new fluid. The result was that by only replacing the fluid with new fluid, the μ -v slope was recovered to the initial value as shown in **Fig. 3**. Based on this, it was evident that the main factor causing shudder was a functional decline of the fluid.

Figure 4 shows the chronological change of the elements in the commercialized ATF before and after the durability test. The characteristic elements in the fluid by

ICP analysis were as follows: Ca, which is considered to be an ingredient of Ca type metallic detergent, P in the P type extreme pressure additive, and Fe from clutch wear. In **Fig. 4**, it is obvious that as Fe increased, Ca and P decreased markedly. In addition, an FT-IR analysis was conducted for hexane insoluble matters in the remnant debris, with a result that an absorption band at 1 100 cm^{-1} was identified indicating iron phosphate. From this result, it was inferred that the fluid anti-shudder life was compromised by reduction of such main ingredients of the additives as P and Ca due to their reaction with the active iron debris into insoluble matters.



Fig. 2 Change over time of μ -v slope



Fig. 3 μ -v slope in case of fluid change after shudder occurrence (commercialized ATF)



Fig. 4 Change over time of elements in fluid

In an attempt to verify the above-mentioned mechanism, the commercialized ATF and sample fluid without Ca and P type additives were subjected to a μ -v characteristics test on paper type wet clutch proper, with resultant initial μ -v characteristics shown in Fig. 5. It was noted that the fluid without Ca and P additives had negative μ -v slope even in the initial stage, and shudder was generated. Also, there is literature reporting that Ca type metallic detergent is instrumental to extending antishudder life^{6), 7), 9)}, as well as increasing the coefficient of friction in the high sliding speed domain while decreasing it in the low sliding speed domain (positive μ -v slope)^{10), 11)}. Putting these findings together, it is inferred that the reduction of main additives, like Ca and P types, is implicated in deterioration of shudder-prevention capability.



Fig. 5 Influence of additives on μ -v characteristics

3. 2 Optimization of Main Additives

From the analysis of the fluid after the actual device test and the verification test, it has been found that the reduction of P type extreme pressure additive as well as Ca type metallic detergent due to mixture of iron into the fluid leads to decline of anti-shudder life of the ITCC. These findings suggest that improvement of wearresistance characteristics is effective for extension of antishudder life. Therefore, we set out study for optimization of quantity and kinds of P type extreme pressure additive and Ca type metallic detergent that have influence on the wear-resistance characteristics. In addition, because succinimide type dispersant¹¹ is known to affect the wear performance of ITCC¹², optimization of the dispersant was also included in the study.

The sample fluids prepared for evaluation in terms of anti-shudder capability were those containing the succinimide type ashless dispersant, the FM (Friction Modifier) additive, the P type extreme pressure additive and the Ca type metallic detergent with increased quantities or optimized sub-types. Detailed effects of the base oil will be discussed later in this paper.

These sample fluids are summarized in Table 1.

In this evaluation test using the clutch proper LVFA (Lower Velocity Friction Apparatus), in order to reproduce the actual durability test conditions, iron content was eluted in the sample fluid in the quantity of 0.18 mass% which correspond to the iron content in the fluid experienced in the actual device durability test. Figure 6 shows the anti-shudder life obtained in the commercialized ATF and the sample fluids A, B and C, in all of which the iron content was eluted. Although details of additives in the commercialized ATF were not certain, the mixture of iron content reduced life significantly, resulting in the generation of shudder after no more than 72 hours into the test, which suggested successful reproduction of accelerated deterioration in the actual coupling. The sample fluid A, containing iron mixture as well as succinimide type ashless dispersant and amine-type FM additive, attained anti-shudder life of 90 hours, evincing the favorable effect of these additives. Further improvement of anti-shudder life to 100 hours was achieved by the sample fluid B, wherein the contents of succinimide type ashless dispersant, P type extreme pressure additive and Ca type metallic detergent were increased, demonstrating the effect of increased content of these additives. Then, regarding the sample fluid C, which contained an optimized Ca type metallic detergent, an anti-shudder life of 170 hours, which was more than 2 times as long as that of the commercialized ATF, was obtained even with iron elution.

 Table 1
 Test fluids

	Commercialized ATF	Fluid A	Fluid B	Fluid C	Fluid D
EP-agent	Phosphorus type	Phosphorus type A			
Phosphorus content (mass%)	0.03	0.03	0.055		
Metallic detergent	Calcium type	Calcium	type A Calcium type B		type B
Calcium content (mass%)	0.01	0.01	0.05		
Ashless dispersant	Succinimide type	Succinimide type A			
Concentration	Unknown	Normal	Increase		
Friction Modifier: FM	Unknown	Amine type A			
Base oil	Mineral	Mineral Synt			Synthetic



Fig. 6 Effect of additives on anti-shudder durability

From the above test results, it has been demonstrated that the use of succinimide type ashless dispersant and amine type FM additive, increase of P type extreme pressure additive and Ca type metallic detergent as well as an optimized kind of the latter are all effective to extend the anti-shudder life of ITCC.

Then, the sample fluids were subjected to another series of tests on the four ball wear-resistance test rig to determine wear-resistance characteristics of each sample fluid. The test was conducted in accordance with the ASTM D 4172 under the condition of rotational speed of 1 800 min⁻¹, load of 294 N, temperature at 80°C and duration of 30 minutes. The test results are as shown in Fig. 7, indicating that the sample fluids A, B and C had successively better wear-resistance performance compared to the commercialized ATF, which was consistent with the order of anti-shudder life performance. This suggests that optimization of main additives contributed to extension of anti-shudder life, not only through structural stability of the additives themselves, but also through restraint of clutch wear that produces iron debris. Also it is obvious that such improvement in wear-resistance may be attributed to the optimization of quantity and kind of P type extreme pressure additive and Ca type metallic detergent.



Fig. 7 Comparison of wear resistance in four ball wear test

Figure 8 shows the initial μ -v characteristics of the commercialized ATF and the sample fluid C on the paper wet type clutch proper. From **Fig. 8** it is evident that the

minimum coefficient of friction of the sample fluid C was approximately 6% below that of the commercialized ATF. This is due to FM additive and Ca type metallic detergent that are instrumental to reduce coefficient of friction in the low sliding speed domain. The content of these additives were adjusted within the permissible range in the actual device. Furthermore, **Fig. 9** shows chronological change of minimum coefficient of friction (at 0.006 m/s) of the above fluid samples. As is obvious in **Fig. 9**, while the sample fluid C initially showed 6% lower coefficient of friction than the commercialized ATF, it stabilized at a comparable or higher level 25 hours into the test.



Fig. 8 μ -v characteristics of commercialized ATF and fluid C



Fig. 9 Change over time of friction coefficient of commercialized ATF and fluid C

Based on the above study, the conceivable mechanism of improvement in the anti-shudder life is summarized as follows. **Figure 10** shows a schematic of possible chemical formation on the sliding surface, as modified from the original model proposed by Tohyama, et al.⁷⁾ As far as the present experiment is concerned, the mechanism through which those additives improve the anti-shudder life seems to be as follows. The P type additive forms an iron phosphate film, and thereon such basic compounds as the metallic detergent and the dispersant as well as the FM additive are adsorbed. It is conceivable that long time availability of this iron phosphate compounds to be adsorbed as well as restriction of Fe elution due

to formation of this iron phosphate film combined to contribute to improvement of anti-shudder life of the coupling. At the same time, the use of a metallic detergent and FM additive, which excel in structural stability, also seem to have contributed.



Fig. 10 Schematic of products on steel plate surface (alteration: literature 7)

4. Reduction of Low Temperature Viscosity

4. 1 Reduction of Base Oil Viscosity

In the endeavor for reduction of low-temperature viscosity of the fluid, it is imperative to take appropriate measures to ensure wear-resistance and freedom from decline of viscosity in the high-temperature range. For wear-resistance under extreme high pressure in the high-temperature range, securing the oil film is critical, as shown in **Fig. 11**, on which the base oil viscosity and the product viscosity have impact. Generally, the higher is the viscosity, the more capable of forming oil film is the oil under extremely high pressure.



Fig. 11 Lubrication model under extreme high pressure

In order to satisfy these needs, we explored the use of synthetic fluid for the base oil. **Figure 12** shows a conceptual scheme of improving viscosity-temperature property by synthetic base oil. By adoption of synthetic base oil, it is made feasible to alleviate the lowtemperature viscosity, while maintaining adequate viscosity at high temperature. On top of that, even without VII (Viscosity Index Improver), favorable viscosity index can be obtained.

Figure 13 shows BF (Brookfield) viscosity values of the commercial ATF with mineral base oil and the sample fluid D with synthetic base oil. At -40° C in the low-temperature range, the sample fluid D showed dramatic reduction of BF viscosity, i.e. 80% reduction compared to the commercialized ATF.



Fig. 12 Improvement of viscosity-temperature property using synthetic fluid (conceptual scheme)



Fig. 13 Comparison of dynamic viscosity (bf) in low-temperature region

On the other hand, decline of the kinematic viscosity in the high-temperature range is susceptible to deterioration of wear-resistance and leakage of fluid through the seal. In this fluid development, therefore, we set forth the target of high-temperature viscosity corresponding to the viscosity level of the commercial ATF after actual coupling durability testing taking into account the favorable performance of this fluid including aging change in practical application. Namely, it is important to design with the aim of preventing kinematic viscosity from declining below 4.2 mm²/s.

Figure 14 shows a comparison of the stability of kinematic viscosity at 100°C at various shearing times. For evaluation of shearing stability, SONIC (ultrasonic) shearing was employed. As shown in **Fig. 14**, while the commercialized ATF showed notable decline of kinematic viscosity at 100°C due to shearing deterioration of VII, the sample fluid D with synthetic fluid, though without VII, showed stable viscosity no matter what the shearing time was. Also it was revealed that the kinematic viscosity of the sample fluid D satisfied the target of 4.2 mm²/s. Thus, the adoption of synthetic base oil helped achieve dramatic reduction of viscosity at extremely low temperature while securing stability of kinematic viscosity in high temperature range including aging deterioration.

Figure 15 shows the result of comparative heatresistance test (Indiana-Staling oxidation stability test) on the commercialized ATF and the sample fluid D. In this test, the oxidation stability change of each fluid was evaluated comparatively at 165° C for 150 hours. From Fig. 15, the sample fluid D did not have any increase of acid number, indicating exceptionally good heat-resistance compared to the commercialized ATF. Incidentally, the reason for the negative value of the acid number change is assumed to be deterioration of acid substances.



Fig. 14 Shear stability of commercialized ATF and Fluid D



Fig. 15 Comparison of total acid number increase between commercialized ATF and fluid D

Thus, sample fluid D is considered to help restrain the reaction with Fe and main additives, and thereby to contribute to improvement of anti-shudder life.

5. Performance Evaluation on Actual Coupling

5. 1 Evaluation of Anti-Shudder Life and Temperature-Dependence of Maximum Torque

The anti-shudder life evaluation test was conducted on various fluids using an actual ITCC unit. **Figure 16** shows the chronological change of the μ -v slope through the durability test on the commercialized ATF and the sample fluid D, without elution of iron. From **Fig. 16** it is evident that sample fluid D showed dramatic improvement in anti-

shudder life over the commercialized ATF. It was also found that the anti-shudder life of the sample fluids A, B and C in this test was in the same order as experienced in the clutch proper LTFV test mentioned earlier.

After the durability test of commercialized ATF and the sample fluid D, wear on the steel plate was measured with results as shown in **Fig. 17**. The wear ratio was determined by the change of steel plate thickness before and after the durability test. Based on **Fig. 17**, the sample fluid D was found to have restrained wear better than the commercialized ATF, which was consistent with the above-mentioned mechanism.



Fig. 16 Change over time of μ -v slope



Fig. 17 Comparison of wear ratio after durability test



Fig. 18 Relationship between maximum torque and temperature

Figure 18 shows the temperature-dependence of the maximum torque in the actual device test using the

commercialized ATF and sample fluid D, revealing successful reduction of maximum torque in the lowtemperature range by fluid D.

In summary, fluid D, which has drastically improved anti-shudder life while reducing the maximum torque in the low-temperature range, helped make ITCC more compact with higher capacity, thereby reducing the rear drivetrain weight for further improvement in fuel economy of the vehicle. On top of that, it ensures highly reliable performance in the region where the operating environment is severe.

The exclusive coupling fluid TIF was developed based on the concept underlying sample fluid D. Finally, the ITCC incorporating the TIF have been in commercial production since October 2005, expanding their market among auto manufacturers in Japan and overseas.

6. Conclusions

- (1) The shudder generation mechanism in ITCC was found to be caused by degradation of anti-shudder capability from reduction of the P type extreme pressure additive, Ca type metallic detergent, and succinimide ashless dispersant as insoluble contents due to their compounding with the iron content.
- (2) As the anti-shudder prescription of the fluid, it was confirmed that the increase and optimization of P type extreme pressure additive, Ca type metallic detergent, succinimide ashless dispersant and amine type FM are effective, based on which an exclusive fluid which enabled more compact high capacity design of ITCC was developed.
- (3) Reduction of fluid viscosity in the low-temperature range was achieved through optimization of synthetic base oil.

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