

Creation of Technology for Prediction of Self-Excited Vibration under Operating Conditions for Multiple-Plate Clutches

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ABSTRACT

It is important to grasp the dynamic frictional characteristics of facing materials, their methods of use, and the damping characteristics of the drivetrain in order to predict self-excited vibration in multiple-plate clutches used in transmissions. A dedicated torque transmission characteristic test apparatus capable of equalizing the surface pressure was built to deal with the dynamic frictional characteristics of the facing materials, which are affected by the temperature and contact pressure of the friction surfaces. With this apparatus, the sliding velocity dependence was found for each temperature and surface pressure. The behavior of the actual vehicle was also measured when vibration occurs and loss torque is generated by friction in the drivetrain, and damping characteristics were determined from the measurement values. An FEM model of the clutch for the purpose of gaining a quantitative grasp of the dynamic frictional characteristics and methods of use of the facing materials obtained in this way was created, and a simulation model for dynamic behavior analysis of the characteristics of torque transmission from a transmission that incorporates drivetrain damping characteristics to the vehicle body was constructed. In order to confirm the usefulness of this method, the construction of a clutch that suppresses self-excited vibration was examined by simulation and the reduction of vibration in an actual vehicle was confirmed.

1. Introduction

The rise in user needs for enhanced fuel economy has been accompanied by demand for transmissions that are lightweight, compact, and low-friction⁽¹⁾. The size of the clutch imposes limits on demands for lighter weight and further compactness, and it is also necessary to consider durability in terms of absorbing a certain amount of heat. There is a known measure for addressing this by maximizing the difference between the internal and external diameters of the disk friction surfaces, thus limiting the amount of heat produced per unit area⁽²⁾. It is known that surface pressure, temperature, and sliding velocity within the friction surfaces are distributed unequally in a radial direction and that these quantities are considerably affected by the friction characteristics of the facing materials of the clutch⁽³⁾. In designing a clutch, therefore, it is important to clarify the distribution of the surface pressure, temperature, and sliding velocity of the clutch friction surfaces and to grasp the friction characteristics of the facing materials themselves.

Another conceivable response to the demand for reduced

friction would be to reduce friction in the drivetrain. This, however, involves a reduction of damping in the drivetrain, which can be disadvantageous in terms of vibration. The vibration that is an issue in the drivetrain includes forced vibration, the frequency of which varies dependently on the speed of rotation, and self-excited vibration, the frequency of which depends on the eigenvalue of the drivetrain and remains fixed.

In the case of forced vibration, the shape and precision of component parts often provide ways of examining the causes of vibration and measures against it. In the case of self-excited vibration, the amplitude of the vibration tends to continue increasing as long as slippage occurs in the clutch. Whether or not self-excited vibration will be produced is determined both by the influence of the slope of the coefficient of friction with respect to the sliding velocity of the clutch sliding surfaces and by the damping characteristics of the drivetrain⁽⁴⁾. Many of the factors involved in quantification of the slope of the dynamic frictional characteristics of the clutch and the damping characteristics of the drivetrain are unknown. In the current state of technology for simulating vehicle vibration, the

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clutch is most often represented by a single coefficient of friction, so that the technology is not yet at the point of allowing for investigation of vibration countermeasures by means of clutch structure at the design stage. Consequently, countermeasures against self-excited vibration to date have been taken from the perspective of limiting the deterioration of facing materials or oil, which affects friction characteristics to a considerable extent^{(5), (6)}. For this paper, therefore, attention was focused on the dynamic frictional characteristics of the clutch facing materials and methods for their use. The clutch was created as a finite element method (FEM) model, and technology for dynamic behavior analysis capable of simulating torque transmission characteristics during self-excited vibration by means of a plant model that includes the damping characteristics of the drivetrain was developed. This clarified the mechanism by which the torque transmission characteristics of the drivetrain are determined and enable quantitative prediction of self-excited vibration.

2. Obtaining a Clear Understanding of Vibration Phenomena

Figure 1 shows the main section of the transmission used for analysis. It has a wet-type starting clutch placed above the driven pulley shaft, and it enables the vehicle to move smoothly from a standing start by controlling the pressure in a hydraulic circuit placed within the rotating shaft.

Figure 2 shows the results for reproduction of vibration in an actual vehicle by the use of oil that has no friction modifiers added to it. The output speed during acceleration from a standing start was subjected to frequency analysis by fast Fourier transform (FFT), and the results indicated that in addition to a forced vibration with a frequency that rises

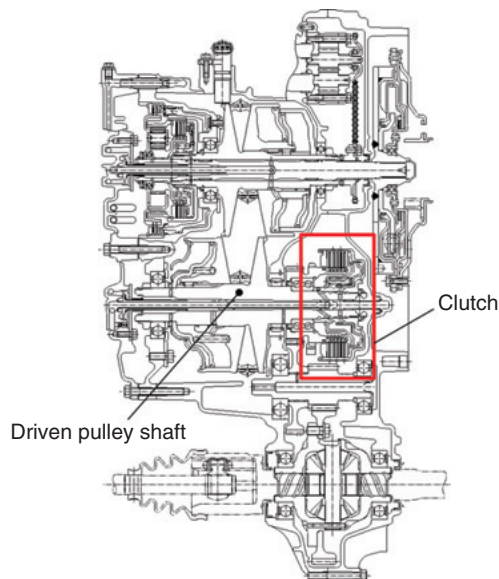


Fig. 1 Main section of transmission

in proportion to the speed of rotation, there was also a self-excited vibration with a frequency that reached a fixed peak independent of the speed of rotation in the range where vibration occurred in the clutch (Fig. 3). Verification was also conducted of torque transmission characteristics from the torque measured on an actual vehicle and the rotational difference in the clutch. This showed a negative slope in the range of rotational difference where vibration occurred, suggesting that torque transmission characteristics with a negative slope with respect to rotational difference were contributing to the vibration (Fig. 4).

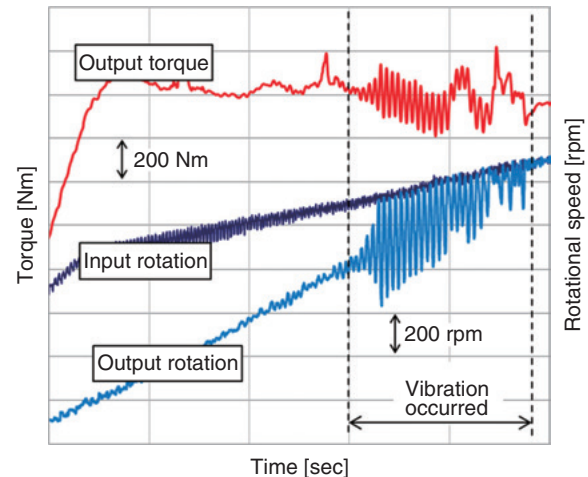


Fig. 2 Self-excited vibration measurement results

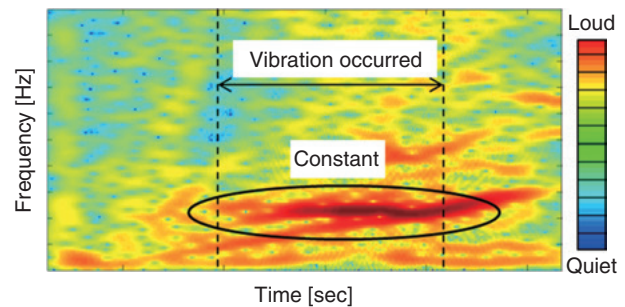


Fig. 3 Frequency analysis of vibration at starting acceleration

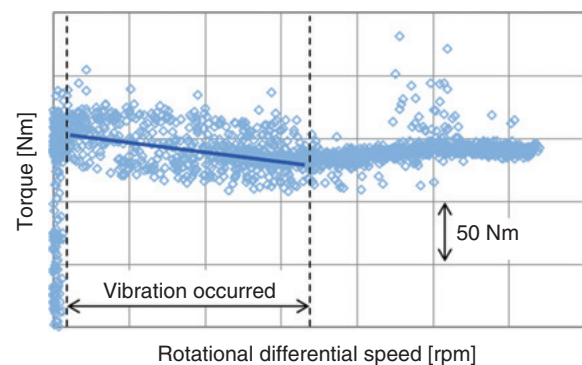


Fig. 4 Torque transmission characteristics

Next, the distribution of surface temperature and surface pressure was investigated in order to determine the state of friction surfaces when vibration occurs in an actual vehicle. In order to measure the temperature of friction surfaces in the course of clutch engagement, thermocouples were embedded in the plates (Fig. 5). The rates of plate temperature increase were different at points A and C on the inside diameter and points B and D on the outside diameter, suggesting that temperature is distributed in a radial direction (Fig. 6).

The distribution of surface pressure was measured using pressure-scaling paper. The results confirmed that, like surface temperature, surface pressure is distributed in a radial direction (Fig. 7).

The surface temperature and surface pressure on the clutch friction surfaces were found from the above to be distributed unequally in a radial direction.

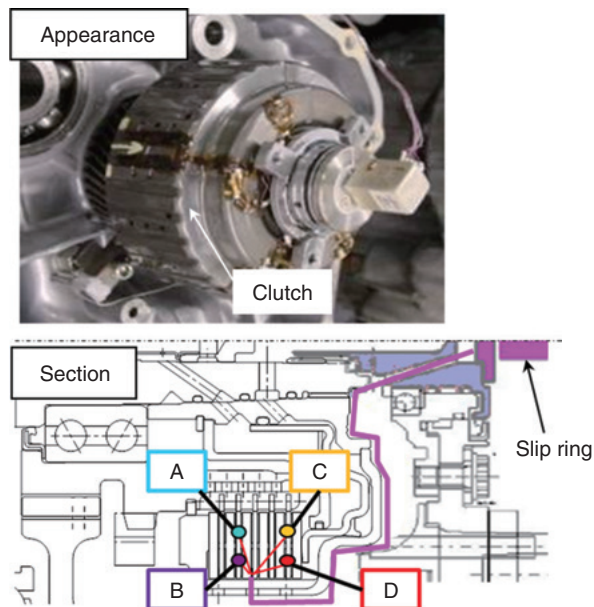


Fig. 5 Measurement points

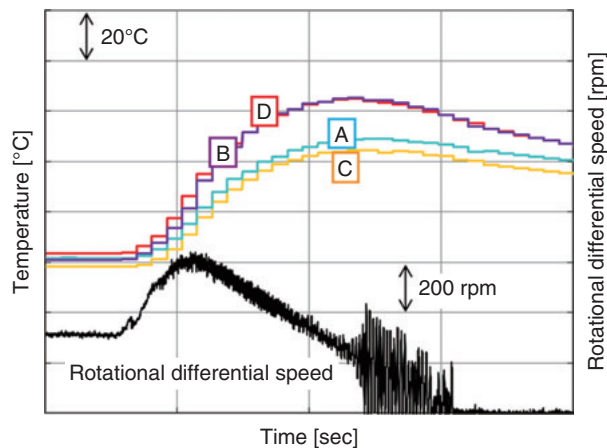


Fig. 6 Plate temperature measurement results

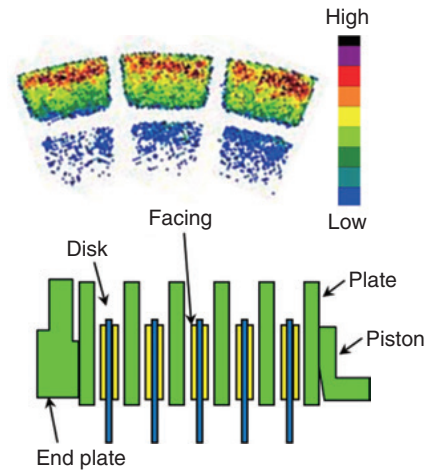


Fig. 7 Facing contact pressure distribution

3. Construction of an Analytical Model of Self-Excited Vibration

The self-excited vibration of the clutch can be described by the equation of motion for the spring-mass system of the drivetrain as a whole (Fig. 8). Here, I is the inertia of the vehicle body downstream from the clutch, K is the torsional rigidity of the drive shaft, T is the transmission torque of the clutch, T_0 is the transmission torque of the clutch in the coefficient of static friction, and θ_1 and θ_2 are the speed of rotation of the driving side and driven side of the clutch, respectively. This calls for the torque transmission characteristics determined by the facing

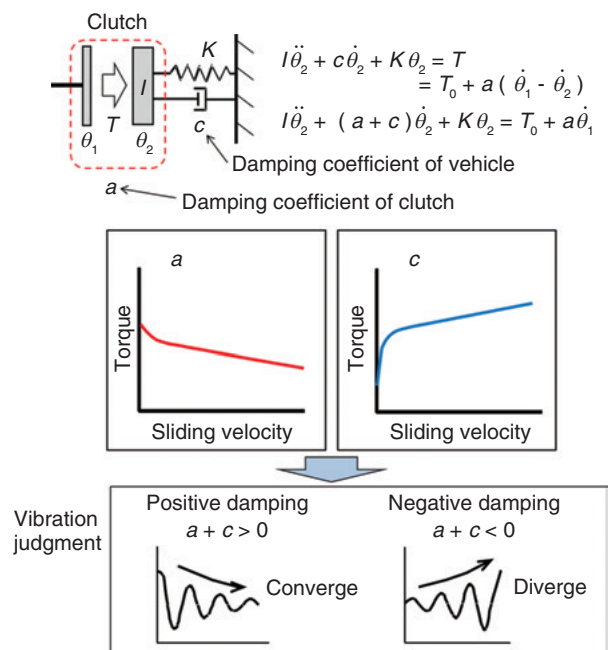


Fig. 8 Hypothesized mechanism of self-excited vibration

materials (slope a in Fig. 8) and the torque transmission characteristics determined by drivetrain damping (slope c in Fig. 8) to be taken into consideration. These characteristics affect the convergence or divergence of the vibration.

The torque transmission characteristics determined by drivetrain damping are thought to always have a positive slope. There are some cases, however, when the coefficient of friction has a negative slope with respect to the sliding velocity in the various parts of the friction surfaces due to variations in friction characteristics and clutch structure as they influence the torque transmission characteristics determined by facing materials. It was inferred that vibration occurs when the sum of those torque transmission characteristics have a negative slope.

The state of the clutch friction surfaces during actual operation was therefore reproduced and a computational model that enables consideration of drivetrain damping characteristics was constructed (Fig. 9). The clutch portion was created as an FEM model, and the distribution of surface pressure, temperature, and sliding velocity of the clutch friction surfaces was taken into consideration. Furthermore, the drivetrain elements before and after the clutch were linked by a one-dimensional torsional vibration system model, which yielded a model for dynamic behavior analysis capable of predicting the vibration of an actual vehicle.

3.1. Dynamic Frictional Characteristics of Clutch Facing Materials

SAE #2 test equipment and LVFA test equipment are known testing devices for measuring the frictional characteristics of clutch facing materials. However, these testing equipment are not readily able to measure frictional characteristics under surface pressure conditions equivalent to those in an actual vehicle. In addition, it is no easy matter to maintain the facing materials as a whole at a fixed temperature. A dedicated torque transmission characteristic test apparatus was therefore created (Fig. 10). By the use of this apparatus, the surface pressure could be maintained at a uniform high range equivalent to that in an actual vehicle, and the friction surfaces could be kept at a uniform overall temperature. This apparatus was used to vary the sliding

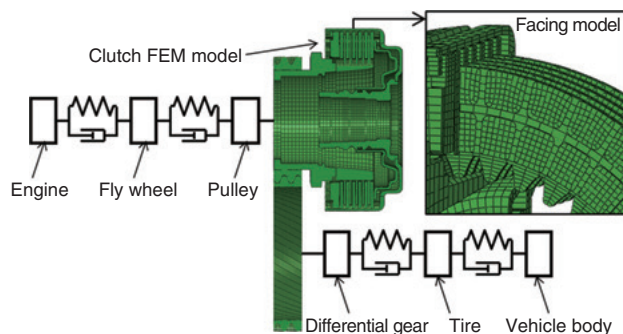


Fig. 9 Self-excited vibration prediction model

Table 1 Conditions of torque characteristics measurement

Contact pressure	0.5 – 6.0 [MPa]
Plate temperature	40 – 180 [°C]
Rotational speed differential	0.5 – 600 [rpm]

velocity and test torque transmission characteristics. The test conditions are shown in Table 1.

Figure 11 shows an example of the torque measurement results. First, hydraulic pressure was added, and then the speed of rotation was raised to the target value. The transmission torque and the temperatures in the various parts of the friction surfaces were measured when the hydraulic pressure and speed of rotation reached a constant state. This test was conducted multiple times under the surface pressure, temperature, and speed of rotation conditions shown in Table 1.

Next, the relationship between dynamic coefficient of friction and temperature at various surface pressures was systematically organized from the measurement results at

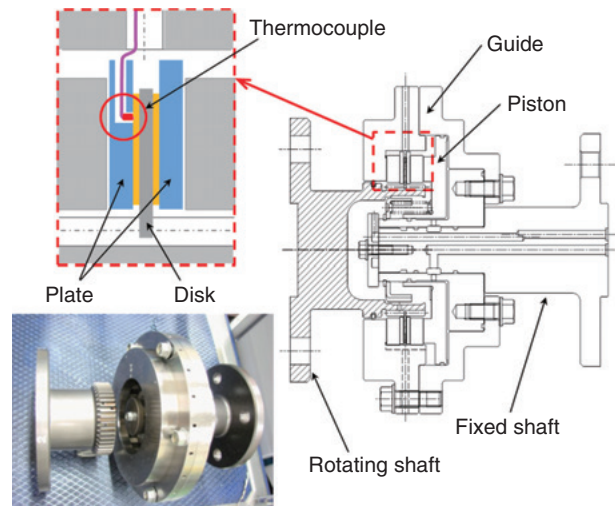


Fig. 10 Test apparatus for torque transmission characteristics

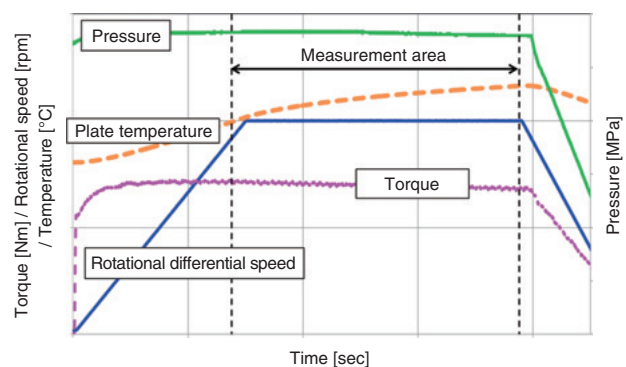


Fig. 11 Results of measurement

various rotational differential speeds as shown in Fig. 12. This was further organized to show the relationship between dynamic coefficient of friction and rotational difference at various temperatures for the various surface pressures.

The relationships between dynamic frictional characteristics of clutch facing materials and rotational difference obtained in this way were organized by surface pressure (Fig. 13) and by temperature (Fig. 14). The dynamic frictional characteristics showed a dependence on surface pressure and rotational difference. A positive slope tended to be found on the lower side of surface pressure and on the higher side of temperature, respectively.

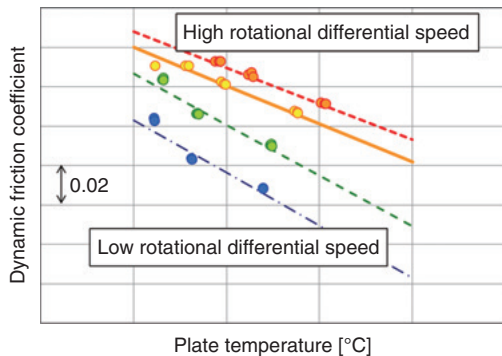


Fig. 12 Friction characteristics

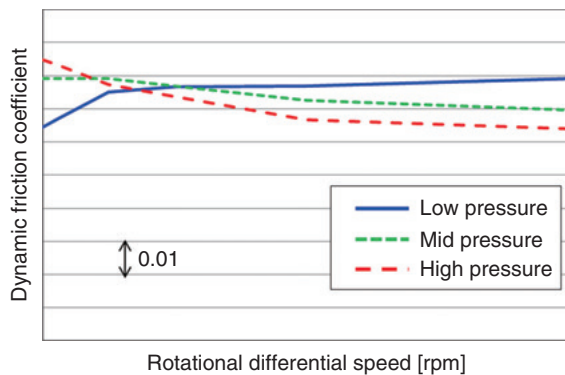


Fig. 13 Influence of pressure in dynamic friction coefficient

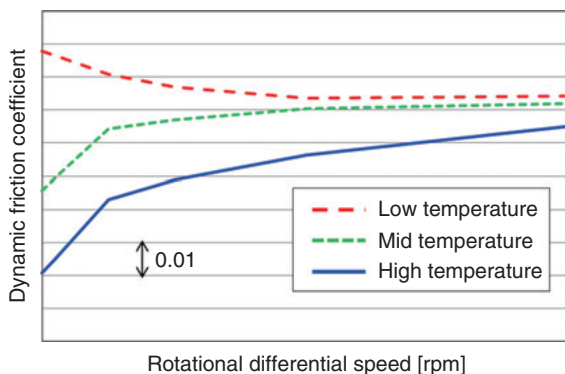


Fig. 14 Influence of temperature in dynamic friction coefficient

3.2. Obtaining a Clear Understanding of Drivetrain Damping Characteristics

When considering damping of the drivetrain as a whole, from the engine to the tires, attention was focused on damping between the clutch and the tires. This is because damping from the engine to the clutch does not affect vibration.

Damping between the clutch and the tires includes friction in the interior of the transmission and differential movement in the differential gear. For the interior friction, the loss torque was measured with the clutch disk and plate removed and the differential gear locked. The damping coefficient was then derived from the relationship between loss torque and rotational speed (Fig. 15).

The damping that accompanies differential movement of the differential gear was identified by both measurement and analysis. Figure 16 shows the results for calculation of the vibration behavior from the speed of rotation of the left and right drive shafts. The drive shafts on left and right are of unequal length, so there is a difference in rigidity. Consequently, when there is no friction in the differential gear, then when vibration occurs, the rotational speed and torque distributed to the left and right drive shafts will be affected by the right-left difference in rigidity even if

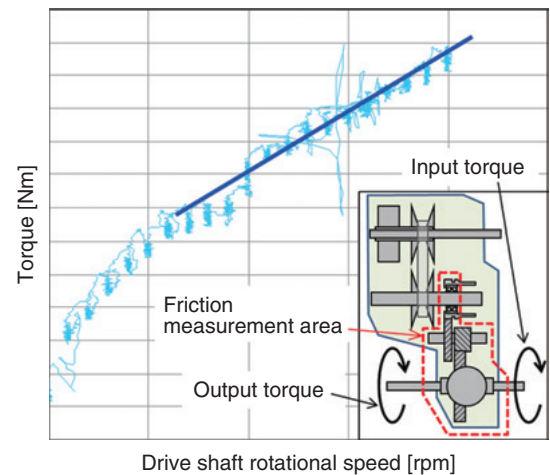


Fig. 15 Measurement of friction loss in transmission

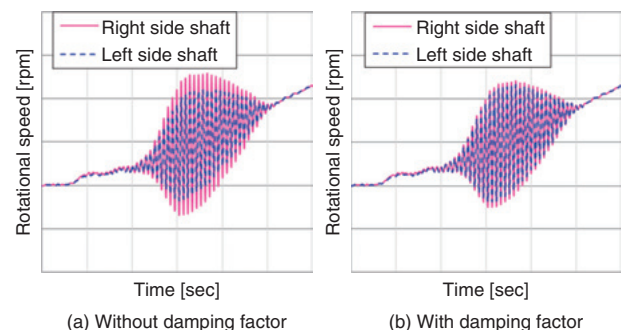


Fig. 16 Effect of differential gear damping factor

the vehicle is moving straight forward, and a difference in vibration behavior will become evident. On the other hand, when there is friction in the differential gear so that a damping effect operates, then the right-left difference in vibration behavior will be reduced, and the effect will be to reduce the influence of the right-left difference in drive shaft rigidity.

Measurements were therefore made of the rotational behavior on the inboard side of the right and left drive shafts of the actual vehicle from which the vibration had been reproduced, with the vehicle moving straight forward. The results showed that the difference in vibration behavior between right and left was infinitesimal, confirming the effect of the friction (Fig. 17). Taking this into account, a theoretical computational model was made of the differential gear vicinity, including damping parameters, and damping parameters that would produce the same rotational behavior as in the actual vehicle were identified (Fig. 18).

3.3. Confirmation of Consistency with Actual Phenomenon

A comparison of simulation results from the analytical model of self-excited vibration using the friction characteristics and damping characteristics described above and the measurement results from an actual vehicle are

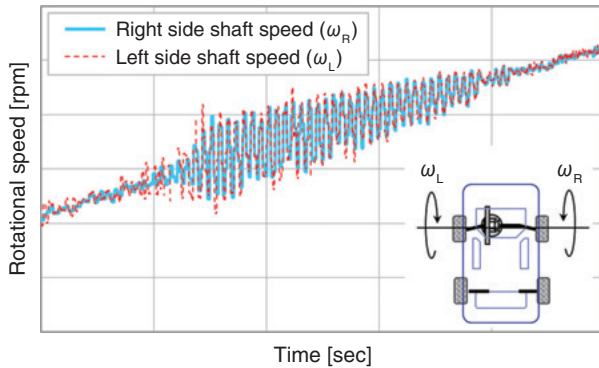


Fig. 17 Measurement of drive shaft speed

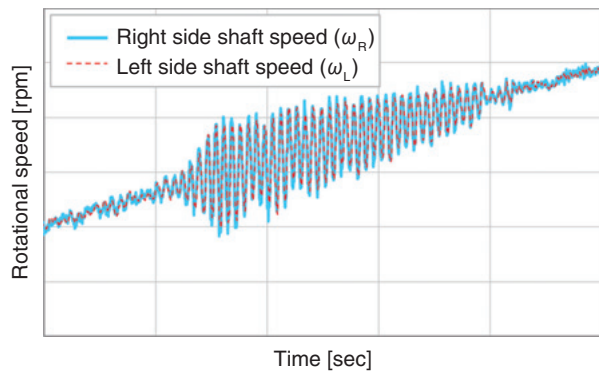


Fig. 18 Identification of damping factor

shown in Fig. 19 and Fig. 20. Verification was conducted using two types of oil, one with and one without friction modifiers, and the occurrence and non-occurrence of vibration equivalent to that of the actual vehicle were reproduced. The verification conducted with oil not containing friction modifiers, in which vibration did occur, showed that frequency, amplitude, and time vibration started were all consistent with the actual measurements.

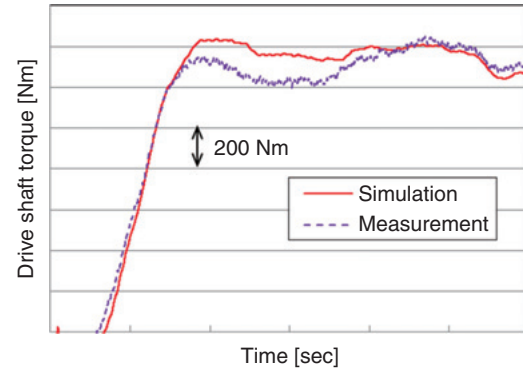


Fig. 19 Torque characteristics (oil with friction modifiers)

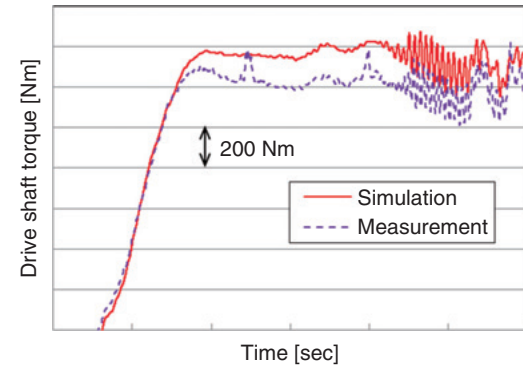


Fig. 20 Torque characteristics (oil without friction modifiers)

4. Validation of Construction Technology

The suppression of vibration was examined from the perspective of construction and based on the conceptual approach of maximizing the use of the range in which variations in dynamic frictional characteristics due to temperature, surface pressure, and sliding velocity produce a positive slope.

With the dynamic frictional characteristics obtained by measurement, the use of the lower range of surface pressure is effective in suppressing self-excited vibration. In terms of temperature, the use of the higher range is effective. However, since the use of the high temperature range has a considerable impact on durability performance, attention was focused on reducing surface pressure.

One conceivable approach to reducing surface pressure without diminishing torque capacity, which is a fundamental aspect of clutch performance, is to increase the number of friction surfaces. However, simply adding disks and plates, and expanding the clutch in a radial direction, would conflict with the move toward compactness. Therefore, the approach of affixing facing materials to one side of both the disk core metal and plates with reduced thickness as well as increasing the number of disks from five to seven was examined as a method that could maintain cooling function and durability without increasing the overall dimensions of the clutch (Fig. 21).

The effectiveness of this approach was validated using oil without friction modifiers so that self-excited vibration could be made to occur more readily. The effect of suppression of self-excited vibration due to the specifications incorporating these countermeasures was verified first by simulation. The results confirmed the reduction of vibration by specifications incorporating countermeasures in desktop estimations (Fig. 22).

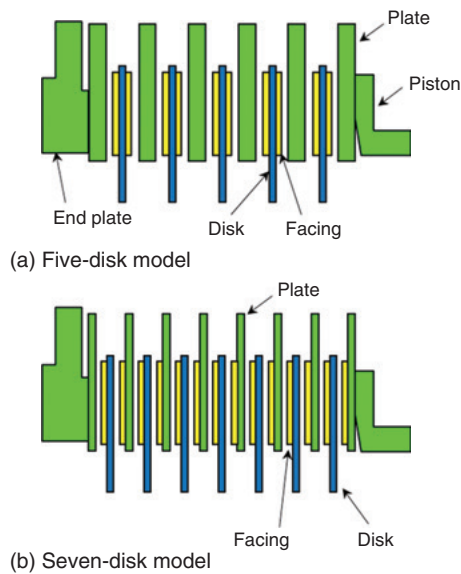


Fig. 21 Section of current and review specifications

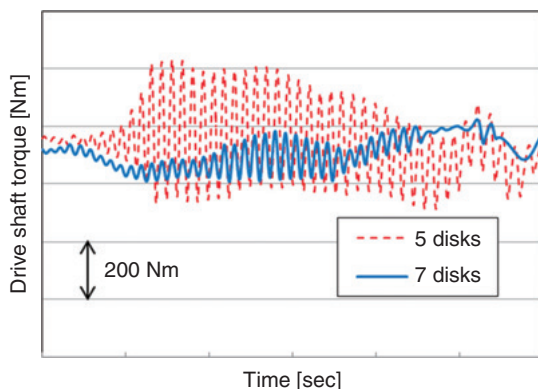


Fig. 22 Calculation results of torque characteristics

This effect was then confirmed on an actual vehicle using these specifications. The results show that vibration was reduced just as in the simulation (Fig. 23). The result of frequency analysis of this vibration waveform also shows a reduction of the peak amplitude in the frequency range where self-excited vibration occurs. This confirmed the usefulness of this method of approach (Fig. 24).

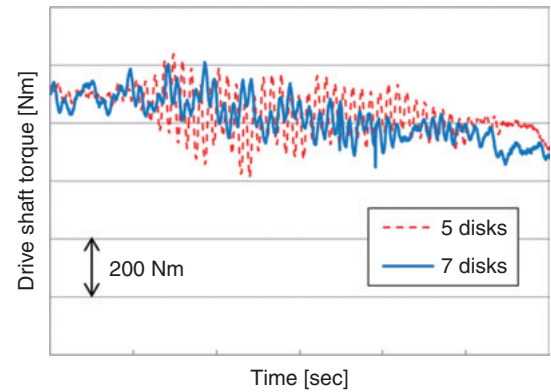


Fig. 23 Measurement results of torque characteristics

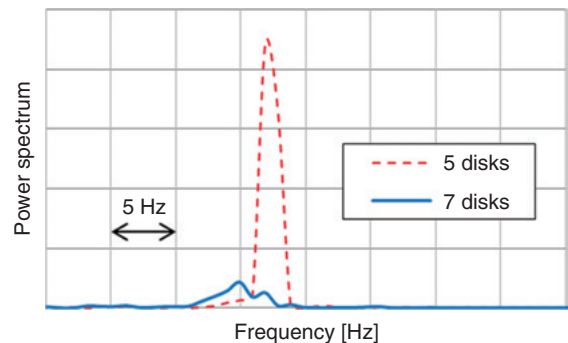


Fig. 24 Power spectrum of measurement results

5. Conclusion

The following conclusions were reached regarding this technology for prediction of self-excited vibration under operating conditions for multiple-plate clutches.

- (1) A model for dynamic behavior analysis was developed with the capability for calculating the torque transmission characteristics of the drivetrain as a whole by using the torque transmission characteristics of the clutch friction surfaces together with the damping values of the drivetrain. This enabled quantitative prediction of self-excited vibration in actual vehicles.
- (2) A clutch construction with an increased number of disks and facing materials affixed to one side of the disks was examined as a method of suppressing vibration. The vibration-suppressing effect this achieved was confirmed both by a model built to perform dynamic behavior analysis and by testing on an actual vehicle.

References

- (1) Yamaguchi, M., Ootaki, M., Ito, K., Nirasawa, H., Totsuka, H.: Development of CVT for 2008 Model Year FIT, Honda R&D Technical Review, Vol. 20, No. 2, p. 12-17
- (2) Saito, T., Kotegawa, T., Matsuura, Y., Tanaka, S., Ohtsuki, K.: Study of Durability Prediction Considering Wear Properties for Multiple Plate Clutches, Honda R&D Technical Review, Vol. 18, No. 2, p. 155-162
- (3) Saito, T., Yamaoka, T., Kato, M., Minaminakamichi, T., Hoshi, T., Miyamoto, K.: Technology for Prediction of Torque Capacity during Operation of AT with Focus on Friction Properties of Facing Materials in Multiple Plate Clutches, SAE Technical Paper 2009-01-1255 (2009)
- (4) Dasai, M.: Noise and Vibration in Wet Brake and Wet Clutch, Tribologist, Vol. 35, No. 5, p. 326-330 (1990)
- (5) Tohyama, M., Ohmori, T., Sanda, S.: Anti-Shudder Mechanism of ATF Additives, R&D Review of Toyota CRDL, Vol. 35, No. 3, p. 43-50 (2000)
- (6) Yatsunami, K., Tersigni, S. H., Saathoff, L. D., Cleveland, C.: Long Life Technology for Automatic Transmission Fluid, Tribologist, Vol. 53, No. 4, p. 236-241 (2008)

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