

Research on Dog Teeth Wear in Dog Clutch Transmissions

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ABSTRACT

In dog clutch transmissions, the excessive wear of dog teeth affects the functions of transmission and becomes a factor to obstruct smooth operation. Therefore, a study was conducted to clarify the wear mechanism of dog teeth by analyzing the operations in transmissions during dog clutch engagement.

In addition, a method of estimating the contact stress applied to the dog teeth was developed, and it was confirmed that contact stress is highly correlated with the degree of dog teeth wear.

Use of the developed method enabled accurate investigation in the early stage of designing on specifications which are related to dog teeth wear.

1. Introduction

Dog clutches are widely used in the stepped transmissions of motorcycles because of the demands for reductions in size and weight, and cost merits. Dog clutch transmissions do not have a synchronizing mechanism, which is applied to synchronized transmissions, for absorbing the rotational speed differences when shifting. Accordingly, a larger load is normally applied to a dog clutch.

In recent years, the displacement of motorcycle engines and their output power have increased, and the moments of inertia of drive train parts and the rotational speed of the transmission operations have been boosted. Through those changes, the load on a dog clutch has been increasing and this increased load makes the dog teeth wear (Fig. 1) larger. Excessive dog wear leads to difficulties in shifting and/or unexpected gear disengagements while driving affecting the smooth riding of a motorcycle.

Meanwhile, the conventional method for mathematical

evaluations on dog teeth wear were generally conducted only by the simplified calculations followed by repeated trials and errors to determine the specifications. With those backgrounds, in this study, we made an attempt to clarify the causal mechanism of dog teeth wear on dog clutches to develop a method of numerical evaluation that enabled the precise estimation of the dog teeth wear progression in order to enhance the development efficiency.

2. Overview of Dog Clutch Transmission

Figure 2 shows a typical dog clutch transmission of a motorcycle. The rider operates the shift lever with his or her left foot to rotate the shift drum via a shift spindle linked to the shift lever. When the shift drum rotates, the shift fork slides in the axial direction of the transmission while the pin on the fork traces the guiding groove situated around the outside of the shift drum. The shift fork arms are positioned to fit the grooves on the shifter with dog teeth, and the shifter slides along the spline on the shaft making the dog teeth engaged.

Before the dog teeth engagement occurs, there is a difference in rotational speeds between the engaging target gear (rotates freely relative to the shaft) and the shifter (spline-fitted onto the shaft), and torque impact is generated when the dog teeth on the gear and the teeth on the shifter make motions for the engagement. At this point of time, if the dog teeth are worn, the axial force is generated (Fig. 3) and the dog teeth jump out without engagement resulting in an incomplete shift maneuver.

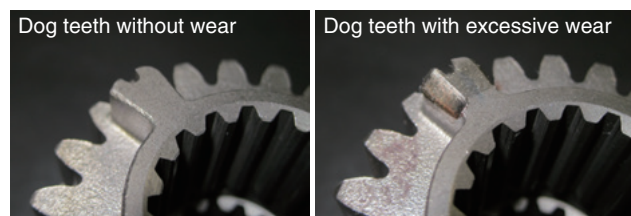


Fig. 1 Dog teeth wear

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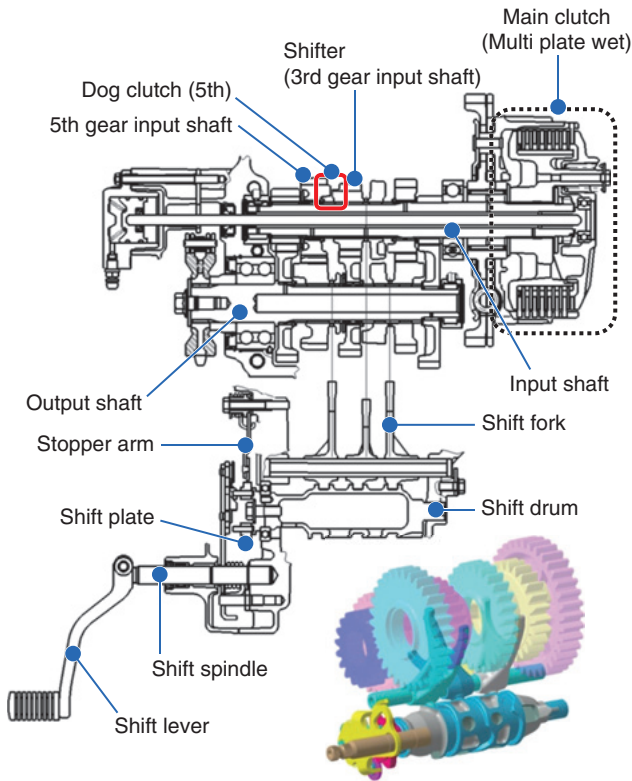


Fig. 2 Structure of dog clutch transmission

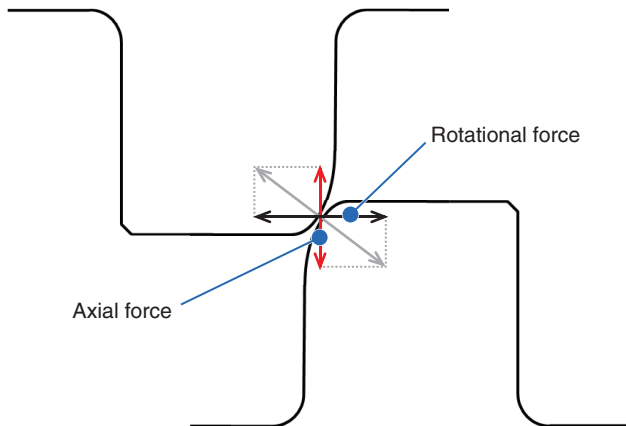


Fig. 3 Axial force on dog teeth

3. Transmission Behavior when Shifting

The behaviors of the transmission when shifting were investigated to clarify the dog teeth wear mechanism. Figures 4 and 5 show a typical example. Data which appear on these graphs are measured at the same time but are separately shown in the different graphs just for ease of comprehension except for the curve showing input shaft torque which is commonly appeared on both graphs.

Figure 4 shows the measurement data for the rotational angles of the shift drum and shift spindle, and the input shaft torque. When shifting, in the first place, the power

delivery between the engine and the transmission is cut off by the main clutch located between the crankshaft and the input shaft. This isolation makes the transmission free from the load and the shift drum begins to rotate in accordance with the rider's operation. When the shift drum rotates, the shifter slides and the dog teeth engage.

When the dog clutch engages, torque fluctuations are generated twice in succession on the input shaft. The shift drum continues to receive rotational force from the rider's operation, but the rider cannot generate large force enough to surpass the resisting torque produced on the input shaft. As a result, the shift drum rotation is stopped. (In the example shown in the figure, the shift drum rotation is stopped at a depth of approximately 30% of the maximum contact depth.) Then, when the torque produced on the input shaft is released, the shift drum begins to rotate again and the dog clutch engages completely.

In this manner, the torque which is large enough to stop the shift drum rotation is occurring at the moment of the dog clutch engagement. The dog teeth contact depth does not change until this torque is released. For this reason, when the dog teeth engage with small contact depth, a large contact stress is generated on the dog teeth contacting surfaces. Since dog teeth wear progresses gradually from the teeth top ends, this load at a small contact depth is thought to be a primary factor of producing wear.

Figure 5 shows the measurement data for the angular velocities of the crankshaft, the input shaft, the output shaft and the rear wheel, and the input shaft torque, where the angular velocities of individual shafts are converted into the equivalent values as those reflected on the velocities on the shaft on which the dog clutch installed. When the drive force is cut off by the main clutch, the input shaft maintains a constant angular velocity with its inertia.

Output shaft maintains its angular velocity as the rear wheel keeps rotating constantly with the stability derived from the inertia of vehicle body mass. The angular velocities of the input and output shafts change abruptly at the instant of the dog clutch engagement, and the two shafts exchange angular momentum, generating the first impact torque. The angular velocity of the rear wheel does not change at this time. It is because the output shaft and the rear wheel are connected by the drive chain that has some slack having them virtually separated at the moment of this first impact (Fig. 6).

Following that, the slack on the drive chain is tightened up with the increase of output shaft angular velocity caused by the first torque impact. At the moment when the slack chain is tightened up, the transmission system and the body system confront to each other, generating the second torque impact as a result (Fig. 6). After the second torque impact is vanished, the third and the fourth torque impacts in negative direction follow. However, those impacts have nothing to do with the wear of the dog teeth because the dog clutch has already fully engaged with the maximum engagement depth (i.e. the angular position of the shift drum has reached to the angle of 60 degrees which is for the next gear position). Consequently,

the first and the second torque impacts are the influencing factors that causes of the dog teeth wear. The second torque impact is smaller than the first one because the torsional rigidity of the body, which has a damper on the rear wheel, is far less than that of the transmission system. Based on this fact, the first torque impact was used in our study for the estimation on the wear amount of the dog teeth by calculating

the contact stress (force per unit area) on the dog teeth.

Meanwhile, it should be noticed that the wear which matters in this case is the one along the direction of the dog clutch engagement motion and the wear amount of dog teeth was defined as shown in Fig. 7, where the wear amount to be evaluated was the sum of the dog teeth wear on the engaging target gear and the wear on the shifter.

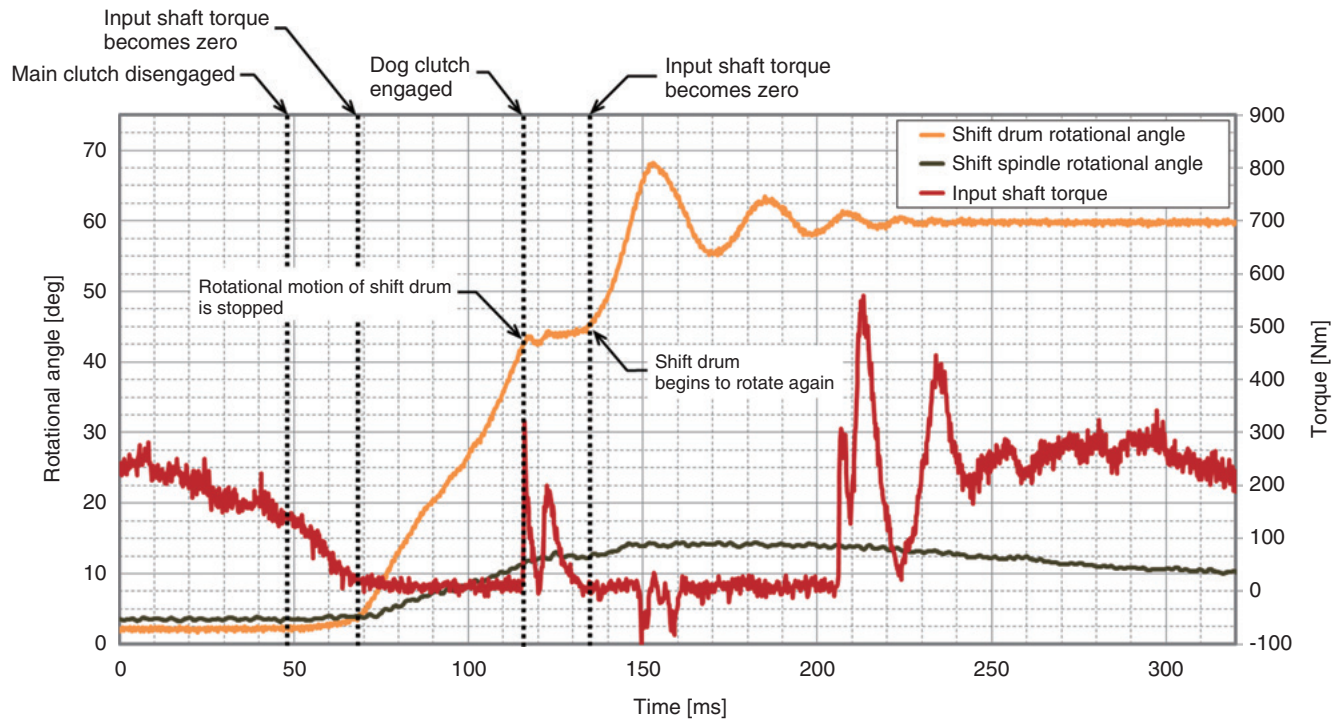


Fig. 4 Time history of rotational angle and torque when dog clutch engages

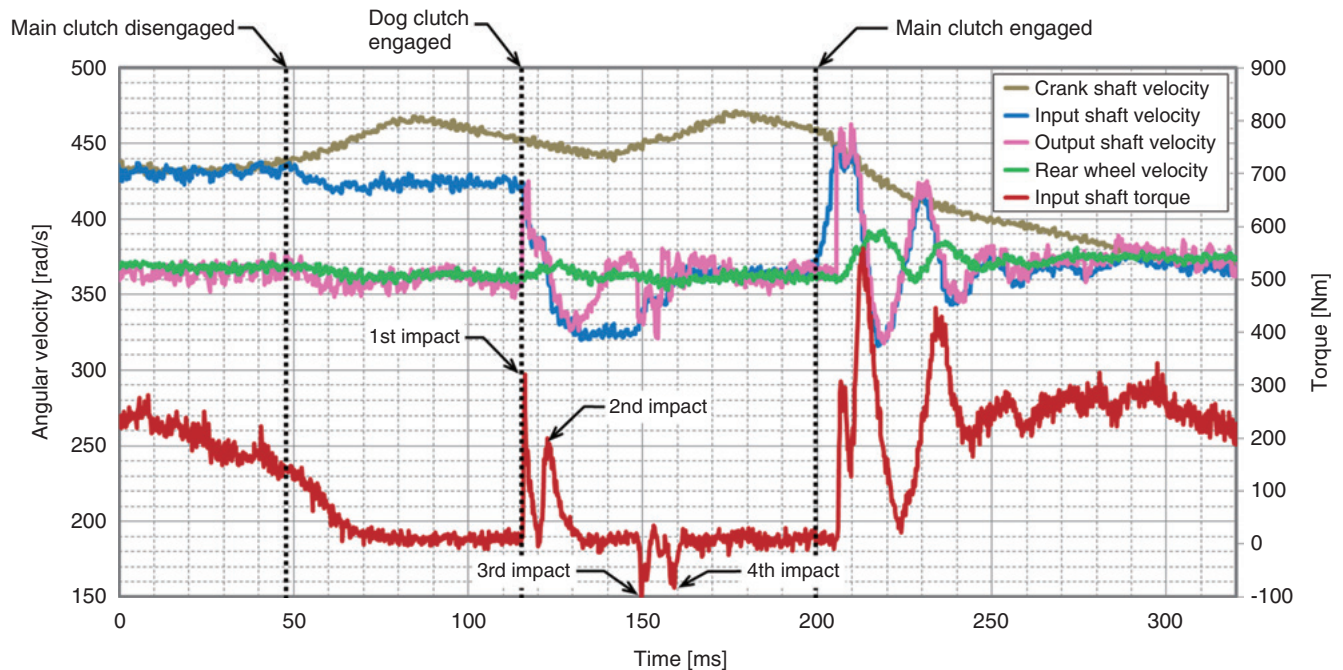


Fig. 5 Time history of angular velocities and torque when dog clutch engages

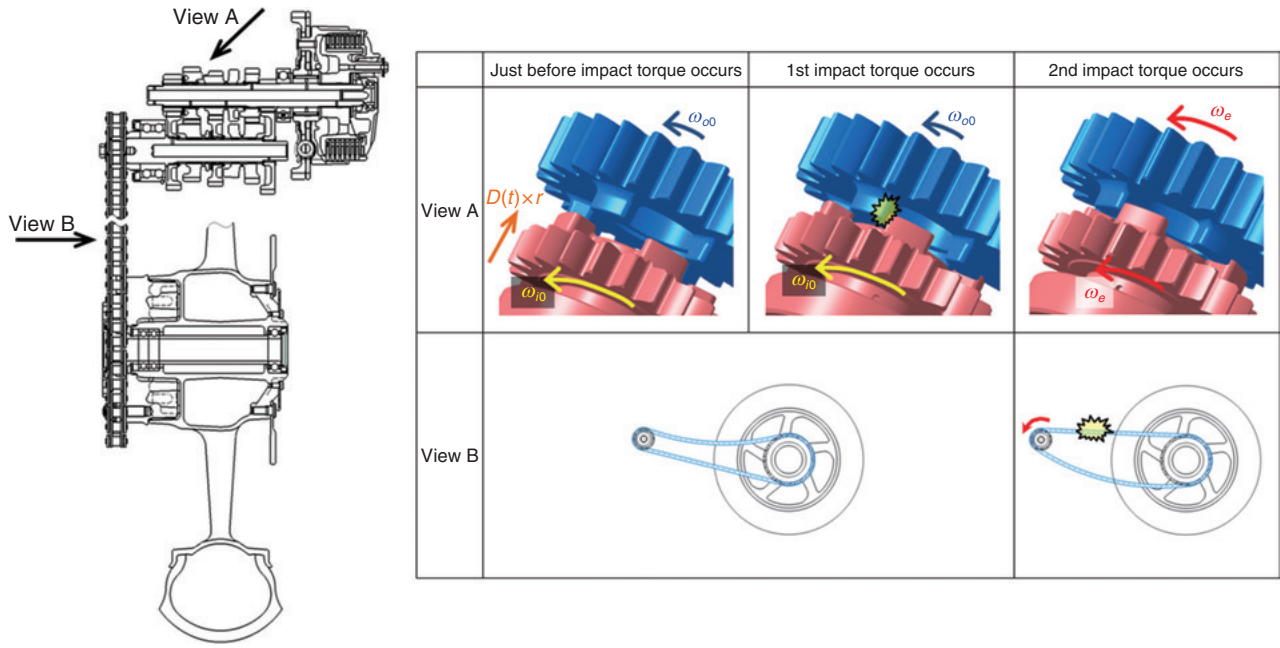


Fig. 6 Transition of drive-system action

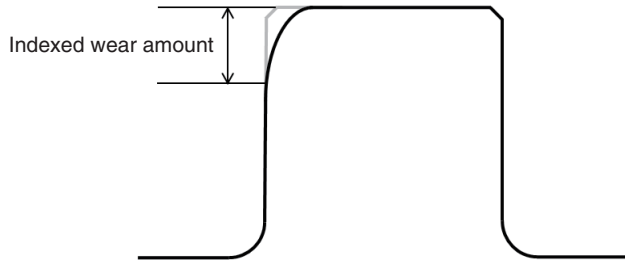


Fig. 7 Definition of Indexed wear amount

4. Torque Impact Associated with Dog Clutch Engagement

To begin with, we considered the first torque impact, which is generated through the engagement of the dog clutch, to analyze the contact stress applied to the dog teeth. The function of a transmission involves multiple dynamic elements, as shown in Fig. 2, with a lot of degrees of freedom, and represents the extreme complexity in its operational behaviors. However, when it is analyzed from macroscopic viewpoint, our research subject can be treated as the collision derived from rotation speed differences between the systems associated with the input shaft and that with the output shaft. Based on this approach of analysis, we estimated the torque impact for the total system converted into just two degrees of freedom for the input shaft system and the output shaft system.

It is easier to understand the kinetics of transmission which is actually a rotational dynamics if it is described as linear motion dynamics model as shown in Fig. 8. Firstly, we made an investigation on the coefficient of restitution to verify

whether or not the attenuation factors have to be taken into account when considering the dog clutch engagement takes place. The test parts were made of low carbon chromium molybdenum steel, applied with carburizing process, which is the same material generally used in the production of transmissions. The coefficient of restitution was 0.98 which is yielded from the data on the angular velocities before and after the collision by conducting the tests excluding the drive chain from the system to eliminate the effects from the body (rear wheel) to the angular velocities of the transmission. Consequently, the equation of motion representing the dog clutch engagement phenomena can be given disregarding the damping terms and is described as below.

$$I_i \cdot \ddot{\theta}_i = K \cdot (\theta_o - \theta_i)$$

$$I_o \cdot \ddot{\theta}_o = K \cdot (\theta_i - \theta_o)$$

Where $t = 0$ at the moment when the input shaft system and the output shaft system just start contacting.

Meanwhile, the torsion spring constant K is defined as the combination of the equivalent torsion spring constant for the input shaft system k_i and the equivalent torsion spring constant for the output shaft system k_o in series and given as:

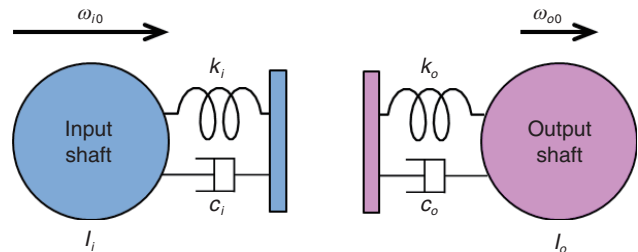


Fig. 8 Impact model

$$K = \frac{k_i \cdot k_o}{k_i + k_o}$$

For the next step, putting the relative angle of torsion between input shaft system and the output shaft system signified as θ ($\theta = \theta_i - \theta_o$), and setting:

$$I = \frac{I_i \cdot I_o}{I_i + I_o}$$

Then the equation of motion can be simply expressed as:

$$I \cdot \ddot{\theta} + K \cdot \theta = 0$$

The initial condition when $t = 0$ can be set as $\theta = 0$ and $\dot{\theta} = (\omega_{i0} - \omega_{o0})$ and the solution of the equation above is given as follows.

$$\theta = \frac{(\omega_{i0} - \omega_{o0})}{\omega_n} \cdot \sin(\omega_n t)$$

$$\omega_n = \sqrt{K/I}$$

Subsequently, by setting the impact torque, experienced when the dog clutch engages, to T and with the assumption that the torque is defined positive when its direction is to accelerate the vehicle, T is described as:

$$T = \omega_n \cdot \frac{I_i \cdot I_o}{I_i + I_o} \cdot (\omega_{i0} - \omega_{o0}) \cdot \sin(\omega_n t)$$

In addition, the maximum impact torque T_{max} is given when $t = \pi/(2\omega_n)$, and T_{max} is presented as follows.

$$T_{max} = \sqrt{\frac{k_i \cdot k_o}{k_i + k_o} \cdot \frac{I_i \cdot I_o}{I_i + I_o}} \cdot (\omega_{i0} - \omega_{o0})$$

I_i : Equivalent moment of inertia of the input shaft system [kg·m²]

I_o : Equivalent moment of inertia of the output shaft system [kg·m²]

θ_i : Equivalent angle of torsion of the input shaft system [rad]

θ_o : Equivalent angle of torsion of the output shaft system [rad]

k_i : Equivalent torsional spring constant of the input shaft system [Nm/rad]

k_o : Equivalent torsional spring constant of the output shaft system [Nm/rad]

ω_{i0} : Equivalent initial angular velocity of the input shaft system [rad/s]

ω_{o0} : Equivalent initial angular velocity of the output shaft system [rad/s]

ω_n : Natural angular frequency [rad/s]

t : Time [s]

T : Impact torque when the dog clutch engages [Nm]

T_{max} : Maximum impact torque when the dog clutch engages [Nm]

By using the actual motorcycle with a displacement of 1000 cm³, the torque was measured, while varying the angular velocity difference when shifting, to verify the accuracy of this equation for maximum torque impact. The measurement was carried out using a strain gauge at the point between the main clutch and the 1st gear on the input shaft. It was confirmed that the measurement error was around 10% in any measurement conditions, including the situations with different gear positions, through the comparisons between the measurement results and the calculated values. As a representative case, the results for the shift-up to the 2nd gear are shown in Fig. 9. The measurement results and the calculated values are showing good correspondence and the calculation method we developed for the maximum impact torque was validated.

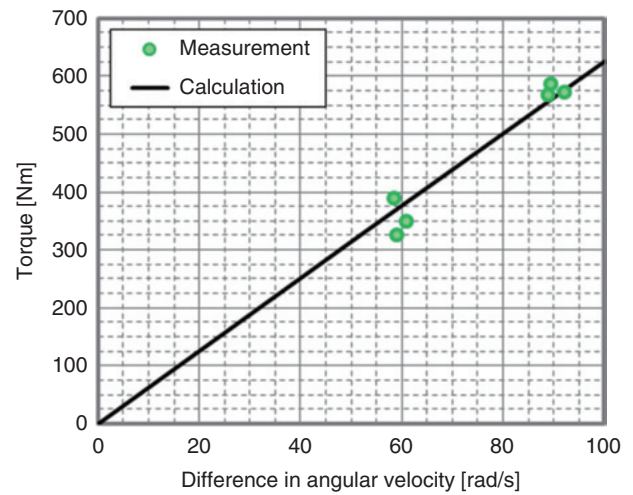


Fig. 9 Relation between impact torque and difference in angular velocity

5. Dog Clutch Engagement Area and Contact Stress

For the next step, we considered the dog tooth engagement area to evaluate the contact stress applied on the tooth. The dog tooth engagement area is defined as the multiplied value of the radial length by the depth of engagement (Fig. 10).

$$A = L \times H$$

A : Dog tooth engagement area [mm²]

L : Dog tooth radial length [mm]

H : Dog tooth depth of engagement [mm]

The depth of engagement H varies depending on the maneuvering characteristics of a rider (the transitional manners of the shift lever movement to the time progression) and the specifications of the dog clutch, while the radial length L can be determined simply from the set value in the design process. Therefore, in our study, we

moved forward to think about the way to calculate the contact stress through the organized investigations on the factors that involve the depth of engagement.

5.1. Shift Lever Operation Characteristics

It is already well recognized that the dog teeth experience significant wear when the rotational speed of engine is high. It is because the higher the engine rotational speed when shifting is the larger the relative rotational speed is, when the dog teeth engage. As the relative rotational speed goes up, the engagement depth gets smaller with the increased torque impact at the engagement. That's why the contact stress on the dog teeth becomes larger and the dog teeth undergo more wear as a result.

Accordingly, in our study, we conducted the tests to analyze the shift lever maneuvering characteristics, which has significant influences on the dog teeth engagement depth, in the tests under conditions of the shift changes at the maximum engine speed with full open throttle when accelerating and, when decelerating, under conditions of the shift changes at the engine speed that is supposed to generate the maximum engine speed after shifting with complete closed throttle.

5.1.1. Differences between situations with and without teeth edge faces contacts

There are two cases for dog teeth engagement. One of them is the case in which the dog teeth experience the contacts on their edge faces to each other. The other case is the case in which the dog teeth engagement occurs without the teeth edges' contacts. The typical data is shown in Fig. 11 for those two cases presenting the shift drum rotation angles with reference to the time. These angular velocity of the shift drum are equivalent until the dog teeth edges reach the position where their contact are about to occur. After that moment, the shift drum continues to rotate at about the constant angular velocity if the dog teeth edges

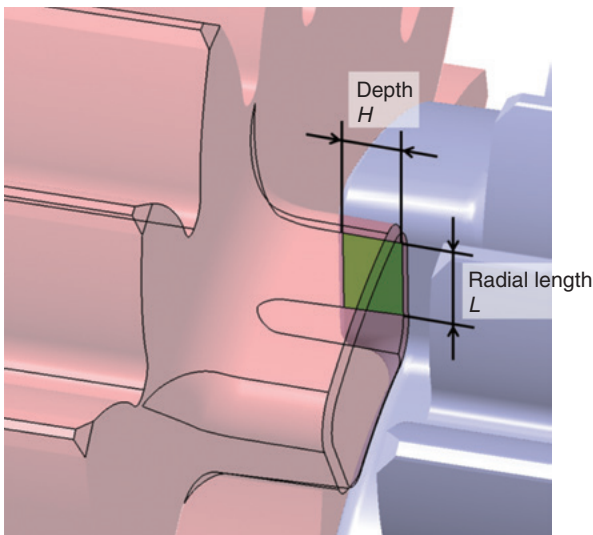


Fig. 10 Contact area of dog teeth

have no contacts. On the other hand, if the dog teeth edges (described as “tips of dog teeth” in figures) experience the contacts, the angular velocity of the shift drum goes down to zero for a short period because the movement of the shifter is inhibited. The shift drum angular velocity gradually increases after the contacts are dissolved. With those facts, it can be clearly understood that the situation with the contacts of the dog teeth edges are different from that of without them. Thus, the characteristics of the shift lever maneuvering are to be separately investigated depending on whether or not the dog teeth edges experience the contacts.

In our study, we conducted the averaging processes to the data of shift lever maneuvering on 10 riders of subjects to get the standardized maneuvering characteristics for shift lever operation. Based on that result, the approximation equation was yielded as shown below.

$$D_1(t) = \alpha \cdot t^4 + \beta \cdot t^3 + \gamma \cdot t^2 + \delta \cdot t$$

$$D_2(t) = \varepsilon \cdot t$$

$D_1(t)$: Displacement of shift lever peg when the dog clutch engaged with the teeth edge faces' contact [mm]

$D_2(t)$: Displacement of shift lever peg when the dog clutch engaged without teeth edge faces' contact [mm]

The time t is set as $t = 0$ at the moment when the dog teeth edges' confronting contacts finish in the case that the dog teeth edges have contacts, and is set, in the case that the dog teeth edges have no contacts, at the moment when the dog teeth advances in the axial direction and reach to the point that the teeth edge surface planes of both opposing dog teeth are aligned in a single plane. Where α , β , γ , δ and ε are the constants derived from the measurement results of the subjects tests.

5.1.2. Shift lever maneuvering characteristics when passing neutral position

In the next step, we examined the situation of shifting accompanied by the passing of the neutral position (hereafter

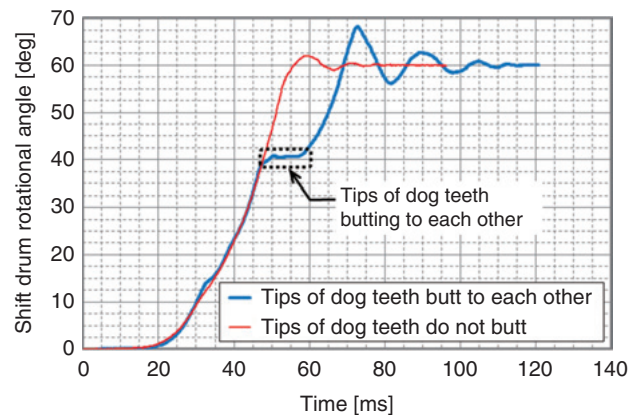


Fig. 11 Comparison of angular transition of shift drum

denoted as N) which is located between the 1st gear position and the 2nd gear position. In Fig. 12, the data of rotational angle of the shift drum is shown with reference to time when shifting from 1st gear position to 2nd gear position. Where 1st gear position corresponds to the shift drum rotational angle of 0 degree, 2nd gear position corresponds to that of 60 degrees and N corresponds to that of 30 degrees. As shown in Fig. 12, it is clearly noticed that the angular velocity of the shift drum varies at around 35 degrees which is the point just after passing N. This is because the roller placed on the stopper arm advances to contact the protuberance corresponding to N on the shift plate on its 2nd gear position side (Fig. 13).

During the shifting, the roller travels over the shift plate smoothly when it is not going through N. However, when there is N on its course, the roller is pushed toward the center of the shift plate by the spring placed on the stopper arm after passing over the protuberance located on the side of the gear position prior to N (i.e. 1st gear position side illustrated in Fig. 13). Consequently, the angular velocity of the shift drum decreases because of the collision of the roller against the protuberance located on the gear position subsequent to N (i.e. 2nd gear position side illustrated in Fig. 13). At this moment, the shift drum angular velocity goes down to zero for an instant and gradually goes up. This phenomenon shows the resembling behavior to the case where the dog teeth edges collide. Accordingly, we

compared the data of the shift drum rotation angle when the dog teeth edges had contacts, as shown in Fig. 11, with the data of that angle when shifting passing through N (Fig. 14). The results showed that the characteristics of those two shift drum rotational angles were equivalent. As a result, we have concluded that the characteristics for the case of passing through N can be evaluated by the characteristics equation $D_1(t)$ which is for the case that the dog teeth engage after edges' collision.

5.2. Contact Stress when Dog Clutch Engaged after Teeth Edge Faces Collision

When the dog teeth edges collide and confront to each other before engagement, the shifting maneuver is restrained during that confronting status lasts. The engagement occurs with the next immediate set of dog teeth when the confrontation of the dog teeth edges is terminated, because of the rotational speed difference, followed by the shifter advancement. The depth of dog teeth engagement can be increased only during the time from the termination of the dog teeth edges' confrontation until the engaging surfaces of the dog teeth reach to the contacting surfaces on the next dog teeth. Setting this time duration as the time available for dog clutch engagement t_s , it is defined by using the difference of angular velocities, the number of dog teeth and the angle of a dog tooth (Fig. 15).

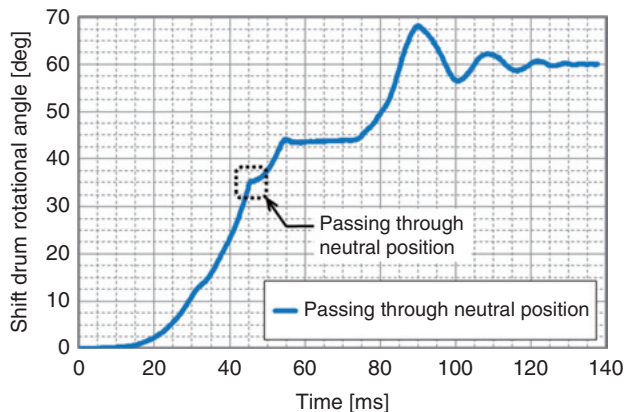


Fig. 12 Angular transition of shift drum in process of passing through neutral position

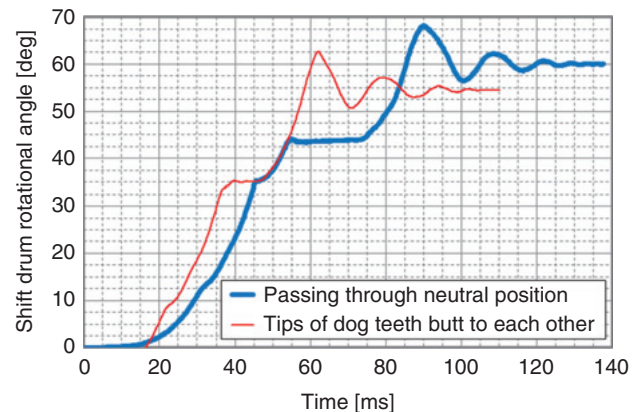


Fig. 14 Comparison of angular transition of shift drum with and without passage through neutral position

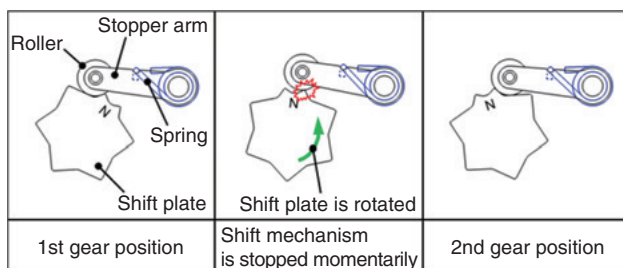


Fig. 13 Transition of shift mechanism action

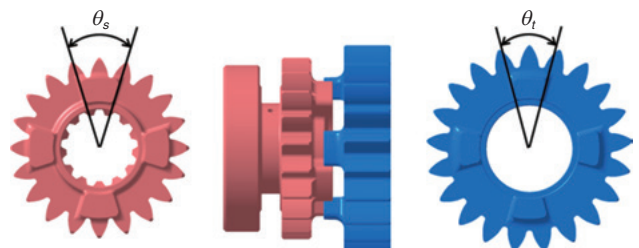


Fig. 15 Angles of dog teeth

$$t_s = \left\{ \frac{2\pi}{n} - (\theta_t + \theta_s) \right\} / (\omega_{i0} - \omega_{o0})$$

- t_s : Time available for dog clutch engagement [s]
 n : Number of dog teeth arranged at even angular intervals around the circumference
 θ_t : Dog tooth angle of engaging target gear [rad]
 θ_s : Dog tooth angle of shifter [rad]

The amount of displacement of the peg on the shift lever caused by a rider's maneuver, in the case that the dog teeth engage after experiencing the teeth edges' contact, can be determined by applying t_s , which is the amount of the time practically used for shifting, to $D_1(t)$. By using the ratio, which can be derived from the values set in the design process, between the displacement of the shifter and the displacement of the shift lever peg, together with the amount of chamfer at the top end perimeters of the dog teeth before use, the area that can be used for the dog teeth engagement is defined as shown in the next equation.

$$A_1 = L \cdot (D_1(t_s) \times r - 2c)$$

- A_1 : Dog tooth engagement area when the dog clutch engaged after the teeth edge faces' contact [mm²]
 r : Ratio between the displacements of the shifter and the shift lever peg
 c : Amount of chamfer at the perimeters of dog teeth top ends of the engaging target gear and the shifter before use [mm]

Consequently, the contact stress σ_1 is given as the equation shown below when the dog clutch engagement occurs accompanying the dog teeth edges' contact.

$$\sigma_1 = \frac{T_{max} \cdot 10^3}{(P/2) \cdot n} \cdot \frac{1}{L \cdot (D_1(t_s) \times r - 2c)}$$

- σ_1 : Contact stress when the dog clutch engaged with experiencing the teeth edge faces' contact [MPa]
 P : Effective diameter of dog teeth [mm]

However, there exists the case in which the value of $(D_1(t_s) \times r)$ exceeds the designed value of maximum possible depth of dog teeth engagement under the condition that the time available for dog clutch engagement is amply long. In this particular case, the area for engagement is defined using the designed value of the maximum dog teeth engagement depth instead of applying $(D_1(t_s) \times r)$.

5.3. Contact Stress when Engaged without Dog Teeth Edge Faces Confrontation

In the case that the dog teeth get engaged without contacts of tooth edges, the depth of the dog teeth engagement varies depending on the angular phase when the dog teeth reach to the point of the opposing dog teeth edge surfaces aligned in a single plane. The maximum engagement depth is brought about when the shifter is

advanced for full of the time available for the depth increase of the dog clutch engagement, which has been mentioned above. The minimum engagement depth is just above 0 mm (where the exact 0 mm cannot be regarded as an actual engagement). The depth of the dog teeth engagement can be any value with the same probability of occurrence within the range between these maximum and minimum engagement depths if the dog teeth do not experience the edges' contacts. Thus dog teeth contact stress can be evaluated using the averaged value calculated based on this range for the dog teeth engagement depth when the dog teeth get engaged without having edges' contacts.

However, the chamfered portions on the dog teeth generate a force component parallel to the gears axis if the engagement depth is smaller than the size of the initial chamfer at unused condition (Fig. 3). In consequence, the dog teeth cannot get engaged in the first chance as the shifter is repelled. The case with this repellent phenomenon should be separately considered and the only cases without repellent are picked up for the investigations of the contact stress here. The contact stress σ_2 is given as in the equation shown below for the engagement cases where the dog teeth edges do not experience the face contacts, by applying 10^{-5} mm for the engagement depth as a adequately small value but larger than 0 mm.

$$\sigma_2 = \frac{T_{max} \cdot 10^3}{(P/2) \cdot n} \cdot \frac{1}{L} \cdot \frac{1}{(D_2(t_s) \times r - 2c) - 10^{-5}} \cdot \int_{10^{-5}}^{D_2(t_s) \times r - 2c} \frac{1}{H} dH$$

- σ_2 : Contact stress when the dog clutch engaged without experiencing the teeth edge faces' contact [MPa]

5.4. Contact Stress when Engagement is Associated with Repellence against Shifter

As described before, the repellence occurs when the engagement depth is smaller than the size of the initial chamfer at the dog teeth edges. Through the investigations of the behaviors of the transmission parts when the repellence occurs, after the disengagement of the dog teeth which follows after the repellence, the dog teeth edges immediately establish the confronting contacts with the counterpart dog teeth edges because the continuing force, delivered through the shift mechanism from the rider's operation, is being applied. Following that status, the dog teeth get engaged with the next immediate counterpart dog teeth with advancement of the shifter when the dog teeth edges' contacts are dissolved. Consequently, when a shifting is accompanied by the repellence of dog teeth, the torque impacts are generated twice for one shifting maneuver but the first torque impact at the dog teeth repellence is not the primary concern about the dog teeth wear in this study because, at that impact, the load is applied only to the limited area of the chamfered portions on the dog teeth edges. With these considerations, our analysis

can be focused on the second torque impact. However, we will firstly describe about the results of the analysis on the repulsion phenomenon that leads to the first impact because the contact stress generated by the second torque impact is under influence of the physics that happens when the dog teeth experience the repulsion.

Through the analysis on the data measured for the cases with dog teeth repulsion (described as “jumping in and out” in figures), the magnitude of the first torque impact varies a lot ranging from a trivial amount to the extremely large quantity (Fig. 16). This variation range of the first torque impacts is defined by the variation range of how much angular momentum can be exchanged at the occurrence of the repulsion. With this relationship, the larger the torque associated with the dog teeth repulsion is the bigger the amount of the exchanged angular momentum is, and that is also translated as the larger exchanged amount of the angular velocity. Based on this analysis, it is likely to be assumed that the second torque impact becomes small when the first torque is large, as the angular velocity difference should have been decreased compared when

the first impact has occurred. However, the reality is that a large torque impact is still observed at the second collision in the dog teeth engagement even when the dog has already experienced a large torque influence through the dog teeth repulsion phenomenon. Accordingly, we decided to investigate the behaviors of the transmission parts when the dog teeth repulsion is happening (Fig. 17).

The angular velocity of the output shaft, which has relatively small moment of inertia, goes up abruptly when the repulsion happens. Therefore, at the moment just after experiencing the repulsion, the difference of the angular velocities sure is small as it is expected. However, the angular velocity, which has once increased after the repulsion, is brought back to the initial velocity before experiencing the repulsion. This is why the difference of angular velocities at the second torque impact becomes much larger on the contrary to the expectation. This is because of the influence from the inertia of the vehicle body delivered through the drive chain which is tightened getting rid of the slack by increased angular velocity of the output shaft. The moment of inertia of the body system is far larger compared to that of the output shaft system, and the angular velocity of the output shaft is brought back to the same speed as the one that corresponds to the movement of the vehicle body, that is to say, the angular velocity before experiencing the repulsion. The amplitudes of the angular velocities of the output shaft are the same at the first and the second collisions of the dog teeth. However, the difference in angular velocities at the second dog teeth collision becomes slightly smaller compared to that for the first collision because the change in the angular velocity caused on the input shaft through experiencing the repulsion has been maintained.

The amplitude of the change in input shaft angular velocity caused by the first impact with the dog teeth

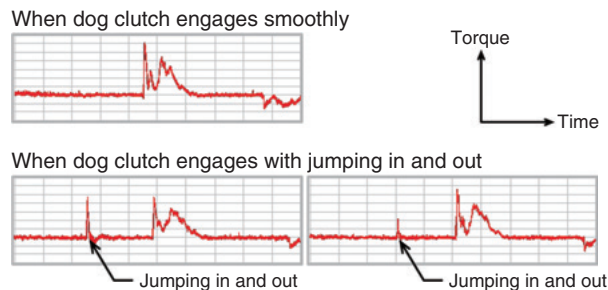


Fig. 16 Time history of torque when dog clutch engages

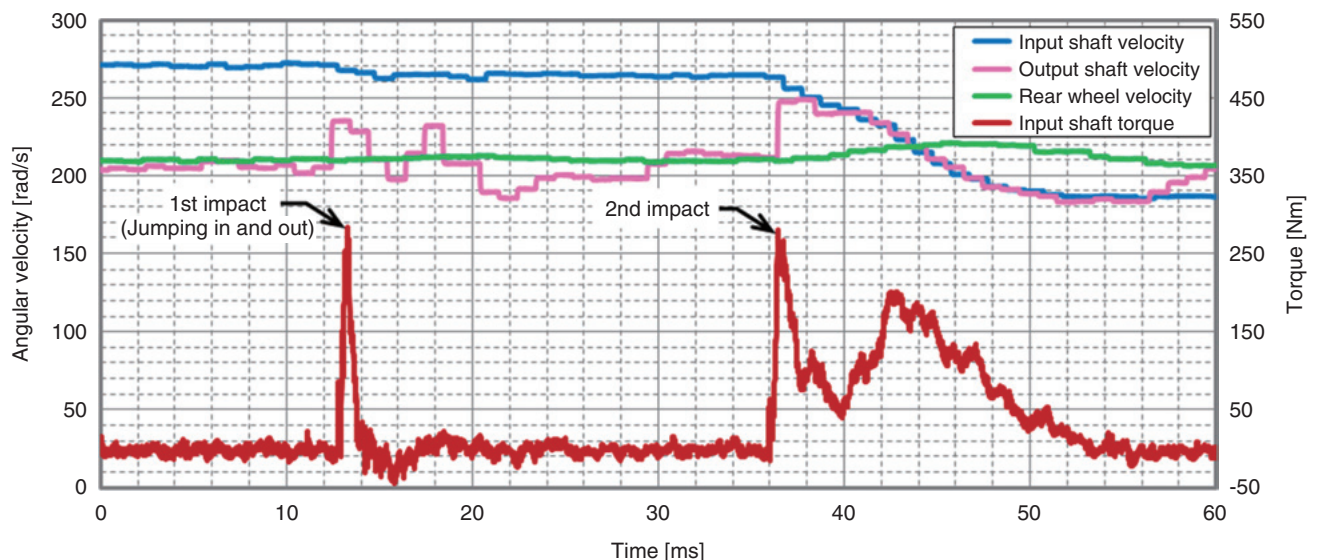


Fig. 17 Behavior of angular velocities and torque when jumping in and out

repellence varies depending on the magnitude of the exchanged angular momentum generated by this repellence. The first torque impact takes the value between 0 to T_{max} because the moment, at which the dog teeth get disengaged with the repellence, appears on the way that the impact torque increases to the maximum value. The angular velocity of the input shaft is the same as the initial angular velocity when the torque impact from the repellence is 0 without accompanying any angular momentum exchange. This is virtually the same as the case without occurrence of the repellence and, in this case, the second impact torque (it is actually not the second impact but the first impact) is T_{max} .

As the next subject, the case in which the magnitude of the first impact torque caused by the repellence reaches to the maximum value (T_{max}) will be considered. This case is the case that the angular velocity of the input shaft decreases the most. It is the moment when the angular velocities of the input shaft and the output shaft turn into the same value that the impact torque comes to the maximum amplitude associated with the first impact from the repellence. Setting the angular velocity to ω_e when this angular velocity match happens, the following formula is derived from the law of conservation of angular momentum.

$$\omega_e = \frac{I_i \cdot \omega_{i0} + I_o \cdot \omega_{o0}}{I_i + I_o}$$

The angular velocity of the input shaft gets ω_e just after the release of the dog teeth engagement when the first impact torque from the repellence becomes its maximum value. Accordingly, the second impact torque T_{min} which follows the first impact is described as in the formula shown below.

$$T_{min} = \sqrt{\frac{k_i \cdot k_o}{k_i + k_o} \cdot \frac{I_i \cdot I_o}{I_i + I_o}} \cdot (\omega_e - \omega_{o0})$$

Based on those mentioned above, T_{mean} which is the mean value of the second impact torque can be given as in the formula below.

$$T_{mean} = \frac{1}{2}(T_{max} + T_{min}) = \frac{1}{2} \cdot \sqrt{\frac{k_i \cdot k_o}{k_i + k_o} \cdot \frac{I_i \cdot I_o}{I_i + I_o}} \cdot (\omega_{i0} + \omega_e - 2\omega_{o0})$$

The area of the dog teeth engagement at the second collision is described as $L \cdot (D_1(t) \times r - 2c)$ because the dog teeth get engaged after experiencing the dog teeth edges' contacts. On the other hand, the angular velocity of the input shaft has already changed from the initial value and the time available for the dog clutch engagement is given as shown in the next formula.

$$t'_s = \left\{ \frac{2\pi}{n} - (\theta_i + \theta_s) \right\} / (\omega_e - \omega_{o0})$$

Consequently, the contact stress when the repellence occurs is shown as the following formula.

$$\sigma_3 = \frac{T_{mean} \cdot 10^3}{(P/2) \cdot n} \cdot \frac{1}{L \cdot (D_1(t'_s) \times r - 2c)}$$

ω_e : Angular velocity immediately after the maximum torque occurs [rad/s]

T_{min} : Minimum impact torque when the dog clutch engages after the repellence [Nm]

T_{mean} : Average impact torque when the dog clutch engages after the repellence [Nm]

t'_s : Time available for dog clutch engagement after the repellence [s]

σ_3 : Contact stress when the repellence occurs [MPa]

5.5. Contact Stress when Passing through Neutral Position

We will move on to the consideration in the case that the shifting maneuver goes over N. Because the characteristics of the shift lever maneuvers are different depending on whether or not the shift operation includes the passing through N, as mentioned above. However, there is no need to consider the influence of the passing through of N because the shifting maneuver is interrupted by the dog teeth edges' contact after passing through N when the engagement takes place following after the dog teeth edges' contact. Thus, we need to consider the influences of passing through N only for the cases in which the dog teeth get engaged without experiencing the edges' contact.

When the engagement is established without having the dog teeth edges' contact, the depth of the dog teeth engagement varies depending on the angular phase at the point that the teeth edge surfaces of the opposing dog teeth are aligned in a single plane. Through the former investigations, it is already known that the characteristic of the shift lever maneuver when passing through N can be evaluated by using the characterization value $D_1(t)$ for the case of the dog clutch engagement with the dog teeth edges' contact (Fig. 14). However, the time required to reach the point that the opposing dog teeth top edges get aligned in a plane should be taken into account because, when passing through N, the point from which the characteristic described by $D_1(t)$ is to be applied is not the same point at which the opposing dog teeth edges get aligned.

The starting point for the application of $D_1(t)$, when passing through N, is the point when the roller on the stopper arm establishes the contact with the protruded part of the shift plate on its side situated to encounter after passing N (Fig. 13). At this exact moment, the dog teeth top edge surfaces are not yet aligned to each other and there still some gap remains between the encountering dog teeth edges. Setting the time required to squeeze the gap to t_c , the maximum value of the dog teeth engagement depth, when experiencing the passage of N, is expressed by $(\{D_1(t_s + t_c) - D_1(t_c)\} \times r - 2c)$. (Where t_c can be defined by following the procedures shown below. In the first step,

the amount of the displacement of the shift lever, which provides the necessary advancement from the position that the roller on the stopper arm gets contact with the protrusion of the shift plate on its side coming after passing N to the position to reach the aligned position of the dog teeth top edge surfaces just before getting into the overlapped arrangement of the dog teeth, is defined by referring to the values already set in the system design. The value t_c can be obtained by putting this displacement to the inverse function of $D_1(t)$.

Consequently, σ'_2 can be defined as the following formula by applying the minimum amount of engagement depth of 10^{-5} mm which is assumed to be a sufficiently small value above 0 mm.

$$\sigma'_2 = \frac{T_{max} \cdot 10^3}{\left(\frac{P}{2}\right) \cdot n} \cdot \frac{1}{L} \cdot \frac{1}{\left\{D_1(t_s + t_c) - D_1(t_c)\right\} \times r - 2c} \cdot \int_{10^{-5}}^{D_1(t_s + t_c) - D_1(t_c)} \frac{1}{H} dH$$

t_c : Time required to squeeze the gap between the edge faces of the dog teeth after passing through N [s]

σ'_2 : Contact stress when the dog clutch engaged without experiencing the teeth edge faces' contact after passing through N [MPa]

6. Estimating Degree of Dog Teeth Wear Caused by Contact Stress

The contact stress applied on the dog teeth varies depending on the cases whether it associated with the top edge surfaces' contact of the dog teeth before engagement, or it establishes the engagement without top edges' contact, or it is the case with the repulsion against the dog teeth. (When it is not associated with dog teeth top edges' contact, whether or not it is accompanied by the passing through of N makes the difference as well.) Accordingly, the combined total contact stress is defined as σ by adding up the contact stresses multiplied by each probability of occurrence of the individual cases.

$$\sigma = \sum_{j=1}^3 \sigma_j \cdot p_j$$

However, in the case of experiencing the passage of N, the evaluation is carried out using σ'_2 instead of σ_2 as the value of the contact stress when the dog teeth top edges' contact does not occur. On the other hand, the probabilities of occurrence for individual cases are provided by following formulae.

$$p_1 = \frac{(\theta_t + \theta_s)}{2\pi/n}$$

$$p_2 = (1 - p_1) \cdot \frac{D_2(t_s) \times r - 2c}{D_2(t_s) \times r}$$

$$p_3 = (1 - p_1) \cdot \frac{2c}{D_2(t_s) \times r}$$

σ : Combined total contact stress [MPa]

p_1 : Probability of the dog clutch engagement with experiencing the teeth edge faces' contact

p_2 : Probability of the dog clutch engagement without experiencing the teeth edge faces' contact

p_3 : Probability of the occurrence of the repulsion

We conducted the durability tests for the actual motorcycles with the displacements of 700 cm³, 900 cm³ and 1200 cm³ in order to verify the relationship between this combined total contact stress and the degree of dog teeth wear. The durability tests are carried out under the test conditions of the shift changes at the maximum engine speed with full open throttle when accelerating and, when decelerating, under conditions of the shift changes at the engine speed which is supposed to generate the maximum engine speed after shifting with complete closed throttle, and the same number of shift maneuvers were performed for each gear position. The carburized low-carbon chromium molybdenum steel, which is commonly used for the production of the transmission parts, was applied for the material used for the test parts. As for the measurement of the dog teeth wear amount, a profilometer was used for the investigations.

The relationship between the contact stress and the dog teeth wear amount after the durability tests is shown in Fig. 18. The significant correlation was confirmed with the correlation coefficient of 0.96 between the contact stress and the dog teeth wear amount.

Through the results mentioned above, the evaluation method based on the contact stress estimation has been proved to be an effective measure which enables the prediction of the dog teeth wear amount with high accuracy providing important information in the process of the design for transmissions employing dog clutches.

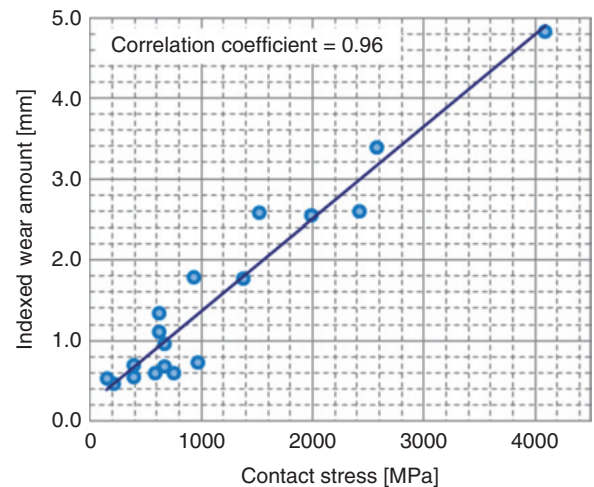


Fig. 18 Relation between indexed wear amount and contact stress

7. Conclusions

The study on the wear of dog teeth in transmission systems with dog clutches was conducted and the following results were obtained.

- (1) The mechanism of the wear associated with dog clutch engagement was clarified.
- (2) The procedure to calculate the impact torque associated with dog clutch engagement was established.
- (3) The evaluation method for the engagement depth associated with dog clutch engagement was established.
- (4) It was made possible to estimate the amount of dog teeth wear through establishing the calculation method to yield the contact stress applied on the teeth of a dog clutch.

Through those results, the investigation on specifications relating to dog teeth wears with high accuracy was made feasible in the earlier stages of the design process.

■ Author ■



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