Technical Report

Development of a method for suppressing CVT chain noise

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Summary

A chain has been increasingly adopted for CVTs in recent years, making the reduction of chain noise a critical issue. A method has been newly developed for suppressing chain noise without changing the CVT hardware. This was accomplished by clarifying that the balance between chain stiffness and pulley clamping force correlates with chain noise.

1. Introduction

The variator that provides the shifting capability of a continuously variable transmission (CVT) consists of a pulley assembly and a belt. There are two kinds of belts; one is more aptly called a pull chain (i.e., chain) and the other is a push belt (i.e., belt). A chain is mainly used on vehicles requiring high-torque capacity (Fig. 1). One advantage of a chain over a belt is lower friction, but chain noise is an issue, which has been addressed by reducing the pitch width or applying noise insulation materials, among other measures.

In recent years, it has become necessary to downsize transmissions even for high-torque vehicles in order to meet the requirements of the automotive industry. Consequently, that has made it necessary to apply large clamping force to pulleys that are now smaller than before. The application of larger clamping force than in the past has caused an issue of chain noise due to microslipping, which is different from previous chain noise. This article describes a newly developed method that can suppress chain noise without changing the CVT hardware.

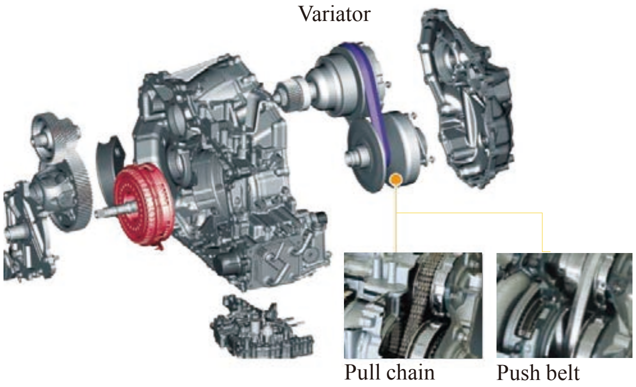

Fig. 1 Structural parts of CVT

2. Chain structure and noise

2.1 Chain structure

Figure 2 shows the structural parts of a chain and the motion that occurs when it curves around a pulley. A chain consists of two types of parts: pins and linkage plates. Two pins combined back-to-back constitute a pair that connects multiple linkage plates to form the chain structure. The adopted structure allows rolling contact between the pins

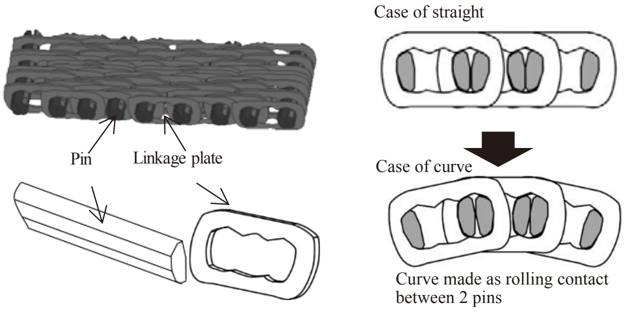

Fig. 2 Structural parts of chain

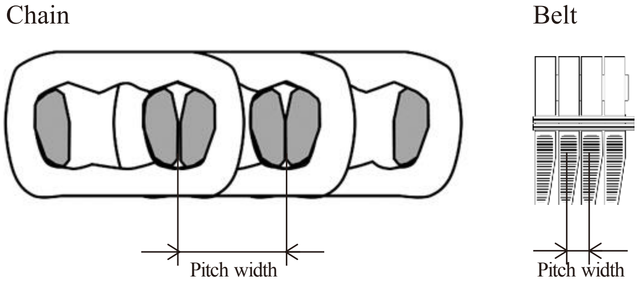

Fig. 3 Comparison of pitch width

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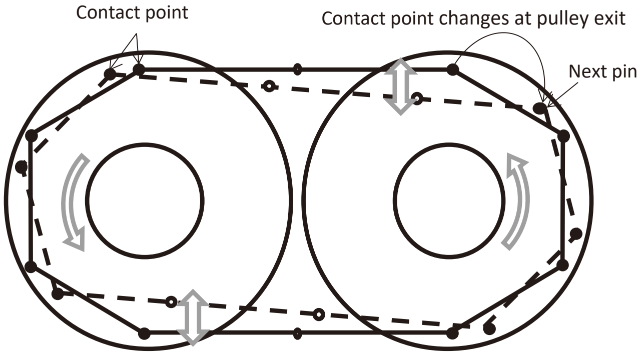


Fig. 4 String vibration due to polygonal motion

when the chain curves, which has the advantage of low friction because frictional losses can be reduced.

Figure 3 compares the pitch width of a chain and a belt. A chain features larger pitch width than a belt. With large pitch width, the chain pins undergo polygonal winding motion as they wrap around the pulley. After a pin in a polygonal winding state exits the pulley, the next pin just behind it supports the chain tension. The repetition of this motion produces string vibration in the chain's straight section, thereby inducing noise (Fig. 4). For that reason, it is known that a chain has a disadvantage regarding noise compared with a belt.

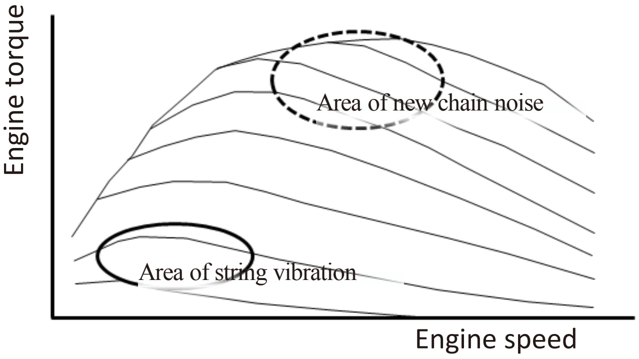


Fig. 5 Areas of chain noise occurring on an engine map

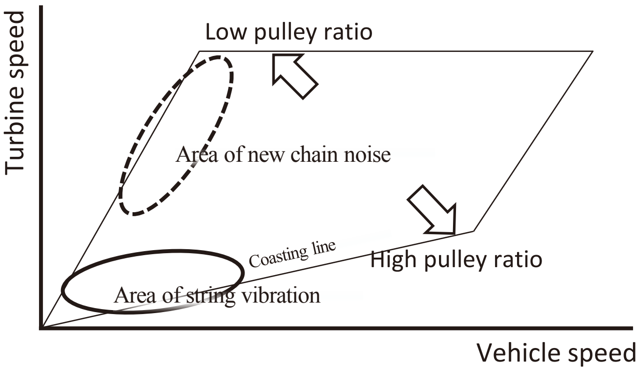
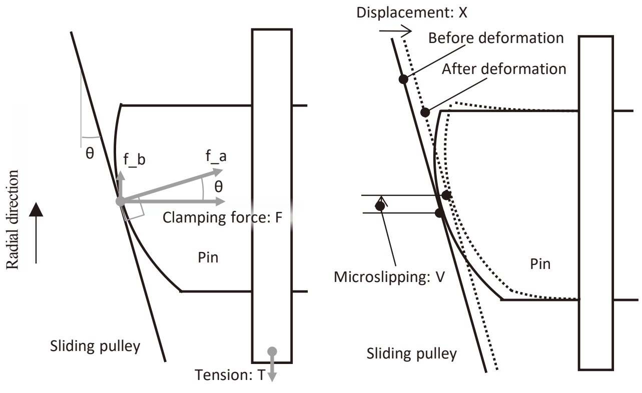


Fig. 6 Areas of chain noise occurring on a shift schedule

2.2 Chain noise

The engine performance map in Fig. 5 shows the areas in which chain noise occurs. The area within the solid line is the region where chain noise has traditionally occurred due to string vibration originating from the pitch width. This chain noise occurs while a vehicle is coasting or gradually accelerating (area within the solid line in Figs. 5 and 6). The reason for that is because string vibration is apt to occur when chain tension decreases in the case of a low torque input.

The new chain noise observed in this development project occurred in a rapid acceleration situation where a low pulley ratio is used (area within the dashed line in Figs. 5 and 6). Because high torque is input to the variator during rapid acceleration, the clamping force is raised to avoid chain slippage. However, applying high clamping force causes microslipping owing to elastic deformation of the chain pins in the pulley radial direction. Because of the chain structure, such microslipping is a phenomenon that has also occurred with previous CVTs. However, it became apparent as a new chain noise in this project because microslipping increased accompanying the reduction of the chain's running radius due to the downsizing of the pulleys. Figure 7 illustrates the force applied to a pin when clamping force is input to the chain and the resultant elastic deformation of the pin. The contact surface of the pulley with the chain pin is called the sheave face. Because the sheave face and the pin come in contact at an angle of 0 deg., the application of clamping force gives rise to f_a and f_b as reaction forces of the clamping force and chain tension. The effect of these forces deforms the pin in the radial direction of the pulley, producing microslipping V between the sheave face and the pin. The contact point between the pulley and the pin at that moment also moves in the radial direction of the pulley, causing axial



(a) Clamping force (b) Deformation of pin

Fig. 7 Pin deformation under clamping force

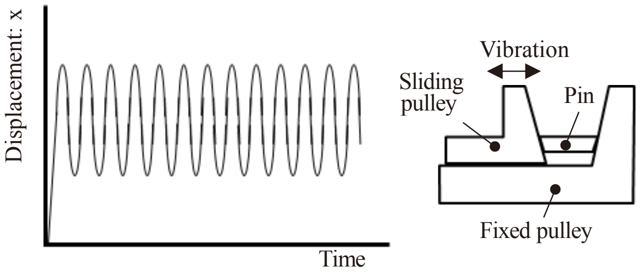


Fig. 8 Vibration of sliding pulley

displacement X of the sliding pulley. Because contact between the chain pins and the sheave face is continuously repeated as the pulley rotates, the axial displacement X of the sliding pulley also repeatedly fluctuates, causing it to vibrate.

The minimum running radius of the chain was reduced in this project accompanying the downsizing of the pulleys. A smaller minimum running radius also reduced the number of pins in contact with the pulley sheave face. For that reason, the clamping force applied to individual pins increased compared with that of previous chains. As a result, it was assumed that axial vibration of the sliding pulley would become larger as illustrated in Fig. 8, thereby leading to the occurrence of chain noise.

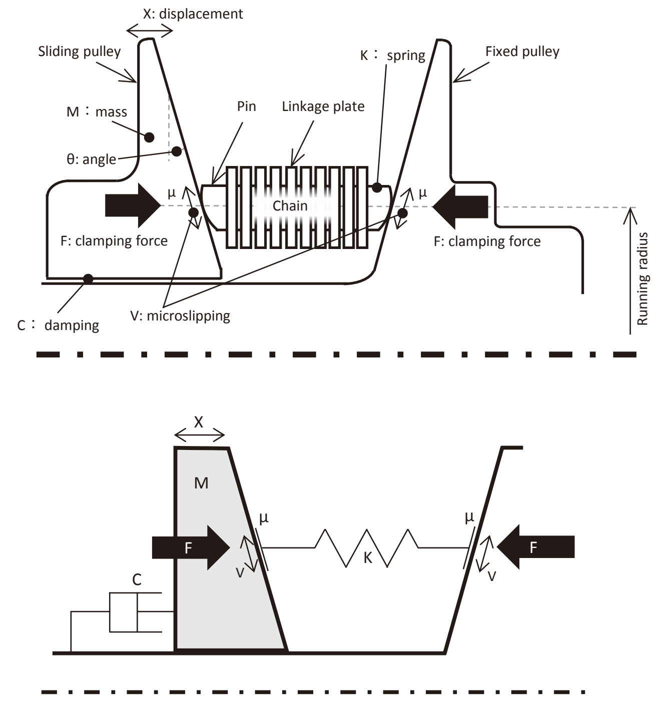


Fig. 9 Modeling of CVT variator

3. Selection of parameters related to chain noise

As described in foregoing subsection 2.2, the new chain noise that became apparent in this project originated from microslipping and was induced by larger vibration of the sliding pulley. In view of this mechanism, it was reasoned that this chain noise could be suppressed by reducing microslipping. The variator was then modeled in order to identify the parameters related to microslipping.

3.1 Modeling of variator

As diagrammed in Fig. 9, the variator was modeled as a damped vibration system for the purpose of identifying the parameters involved in microslipping. The sliding pulley that vibrates was defined as the mass M, the spring constant of the total stiffness of the pins wrapped around the pulley as K, the sliding resistance accompanying movement of the sliding pulley as the damper C, the coefficient of friction between the sliding pulley and pins as μ, the clamping force as F, and the displacement of the sliding pulley due to microslipping at that moment as X.

3.2 Selection of parameters

It was assumed that the new chain noise due to microslipping occurred in the operating region indicated in Fig. 6. Accordingly, it was necessary to suppress microslipping by envisioning various driving situations that occur in this region. In the variator model shown in Fig. 9, the total pin stiffness K that varies according to the running radius and the clamping force F at that moment were selected as parameters that can be controlled during vehicle operation.

- Clamping force F: The clamping force between the pins and the pulley control the torque capacity when the variator transmits torque. Lowering the clamping force

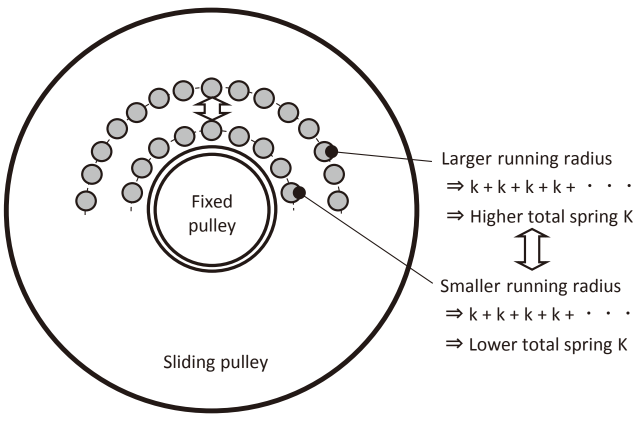


Fig. 10 Total spring K according to running radius

results in insufficient torque transmission capacity. Raising the clamping force excessively, on the other hand, also increases the vibration X of the sliding pulley due to greater microslipping, as explained in subsection 2.2 (Fig. 8). Therefore, it is necessary to set the clamping force suitably so as to both ensure torque transmission capacity and suppress microslipping.

- Total pin stiffness K: In situations where the pulley ratio changes owing to the driving conditions, if the running radius of the chain becomes larger, as shown in Fig. 10, the number of pins wrapped around the pulley also increases. Letting k represent the stiffness of one pin, a parallel spring can be substituted for the pins wrapped around the pulley. The total stiffness K of the pins comprising the parallel spring increases as the running radius becomes larger. The higher the total pin stiffness K is, the more the displacement X of the sliding pulley is suppressed.

4. Confirmation of sensitivity to selected parameters

4.1 Sensitivity of vibration level to clamping force F

An experiment was conducted to ascertain the sensitivity of the vibration level to the clamping force under certain given driving conditions. The vibration level was measured by attaching an acceleration sensor to the side cover of the CVT unit. The experimental results confirmed that a positive first-order correlation existed between the clamping force F and the vibration level (Fig. 11).

4.2 Sensitivity of vibration level to total pin stiffness K

An experiment was conducted to ascertain the sensitivity of the vibration level to the running radius under certain given driving conditions. A larger running radius increased the number of pins wrapped around the pulley, as described in subsection 3.2, which also increased the total pin stiffness K. The experimental results confirmed that a negative first-order correlation existed between the total pin stiffness K and the vibration level (Fig. 12).

5. Proposal and validation of a judgement formula

The sensitivity of chain noise to the clamping force F and the total pin stiffness K was respectively confirmed as explained above. However, these two parameters are interlinked and controlled under actual vehicle operating conditions. Therefore, a judgment formula is proposed here in which the Stribeck equation expressing the relationship between the coefficient of friction and the clamping force is multiplied by the total pin stiffness so as to enable judgment on the basis of a single function. The value thus obtained is referred to as self-excited vibration (SEV).

$$\text{SEV value} = (\eta * V/F) * K$$

where η is the viscosity of the CVT fluid between the pins and the pulley sheave. Figure 13 shows the sensitivity of the side cover vibration to the proposed SEV value when the latter was varied. The experimental results confirmed that increasing the SEV value lowered the vibration level of the side cover. This result indicated that using the SEV

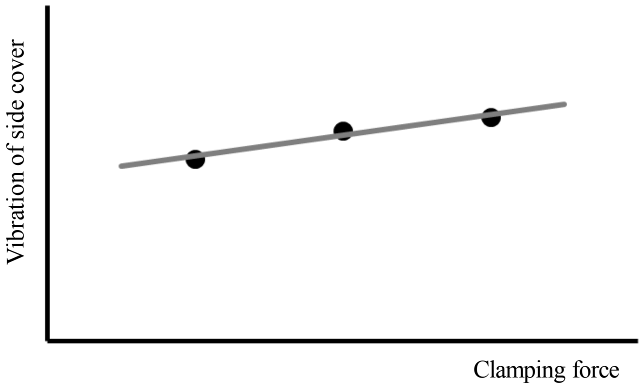


Fig. 11 Clamping force vs. vibration of side cover

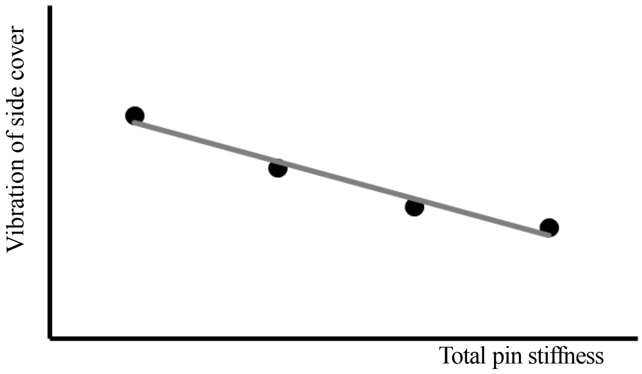


Fig. 12 Total pin stiffness vs vibration of side cover

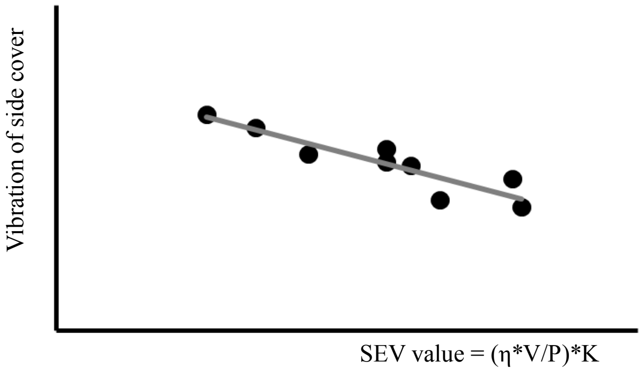


Fig. 13 Validation results for SEV value

value makes it possible to suppress the vibration level in various driving situations envisioned in the area shown in Fig. 6.

6. Conclusion

The minimum running radius of the chain was made smaller than before as a result of downsizing the pulleys in this project. That gave rise to a new chain noise issue caused by microslipping, which differed from previous chain noise. The method developed for suppressing this chain noise without changing the CVT hardware is summarized below.

(1) Downsizing the pulleys increased the clamping force applied to individual pins. It was estimated that this would result in larger axial vibration of the sliding pulley, which would lead to the occurrence of the new chain noise.

(2) It was confirmed experimentally that the vibration level of the side cover had a positive first-order correlation with the clamping force F and a negative first-order correlation with the total pin stiffness K.

(3) Based on the results in (2), the SEV value was proposed as the single criterion of a judgment formula. It was confirmed that the SEV value had a high correlation with the vibration level of the side cover.

The results of this project have been applied to actual vehicles. Using the SEV value as a judgment criterion to suitably control the clamping force and the total pin stiffness has made it possible to suppress chain noise caused by microslipping.

7. References

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