

Simulation of Stress on Elements of Metal Pushing V-belt for CVT under Transient Operating Conditions

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ABSTRACT

The metal pushing V-belt of a torque converter-equipped CVT receives a sudden thrust load from the pulleys when the CVT starts operation, and is required to begin transmitting torque from a stationary state in a very short time span. In the research discussed in this paper, the stress history of the area around the element neck under the transient conditions of CVT start-up was studied using a technology enabling simultaneous simulation of the dynamic behavior of the metal pushing V-belt and stresses on the elements. The results of this study indicated that the load on the V surface of the element is the dominant factor in the generation of stress on the element necks, and that bending stress generated by the pushing force between the elements also acts on the element necks. To confirm the accuracy of the simulation, results were compared with the results of tests conducted to determine the load distribution on the element. The two sets of results demonstrated a good qualitative correlation. This paper also discusses the method employed to evaluate transient stress.

1. Introduction

Against the backdrop of today's intensifying demands for enhanced automotive environmental performance, the CVT is attracting attention from automakers as a transmission type that balances driving performance with high fuel efficiency. In terms of driving performance, CVTs offer quietness and smooth acceleration without shift shock. From the perspective of fuel efficiency, cooperative control between an engine and CVT, to maintain engine speed in the range of higher combustion efficiency, enables the achievement of a level of fuel efficiency surpassing that of an AT. Given this, there will be a requirement to increase the capacity of CVTs in the future^{(1),(2)}. Figure 1 shows a CVT equipped with a torque converter. When a CVT of this type starts operation, a powerful takeoff characteristic generated by a torque amplification effect is balanced with the smooth and open-ended acceleration characteristic that is particularly associated with CVTs.

Vehicle takeoff represents the most severe condition for a CVT in terms of the maximum input torque transmitted to the drive train. The pulleys and the metal

pushing V-belt of a CVT equipped with a torque converter are subjected to a sudden increase in pulley thrust load from a stationary state, and are required to transmit maximum input torque in a minimal amount of time. The most important consideration under these conditions is ensuring the dynamic strength of the metal pushing V-belt. The dynamic strength of the belt is not only determined by the maximum input torque. Consideration must also be given to the ratio and to transient phenomena, such as changes over time in pulley side pressure and pulley speed.



Fig. 1 CVT with torque converter

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However, while there has been a considerable amount of research on transmission capacity focusing on the sliding characteristic of the metal pushing V-belt and the pulleys when the CVT starts up^{(3), (4)}, almost no studies have considered the dynamic strength of the belt itself⁽⁵⁾. This is because it is generally too challenging to measure the dynamic behavior of V-belt and the stress on the elements, parameters that are necessary to judging the strength of the metal pushing V-belt when the CVT is operating⁽⁶⁾.

A previous research project focused on the dynamic stress generated in the rings when the belt is in operation, and developed a technology to simulate dynamic behavior of V-belt⁽³⁾. The effect of the stiffness of the pulleys on ring stress has also been studied⁽⁷⁾. In addition, a method of calculating the detailed stress on the individual elements using the element contact pressure obtained from simulations of the dynamic behavior of the belt has been developed, and the distribution of element stress across the belt as a whole has been elucidated⁽⁸⁾. This paper reports on research that used simulations to elucidate for the first time the stress history on the necks of the belt elements under transient conditions at CVT start-up.

2. Development Goals

Figure 2 shows a cutaway of the main section of a CVT. Drive torque is shifted and transmitted from the drive pulley to the driven pulley by the friction force generated between the belt elements and pulleys. This friction force is generated by the constriction of the belt by the side pressure on the pulleys. The level of stress

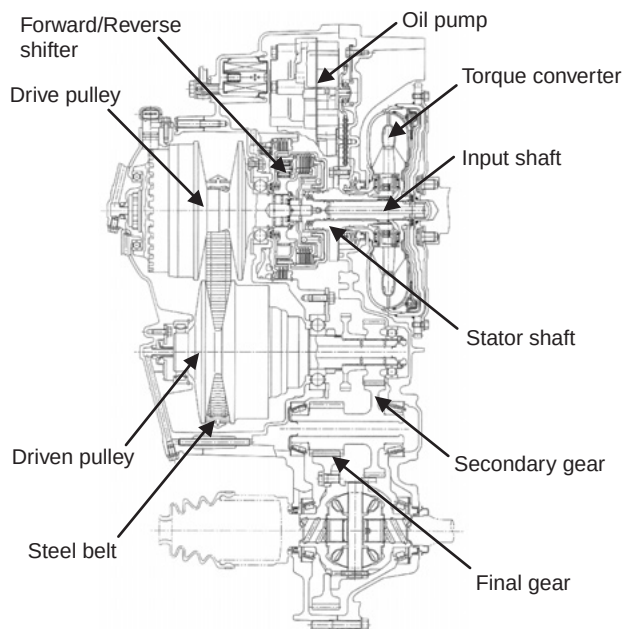


Fig. 2 CVT main section

generated in the rings and elements of the belt when the CVT is in operation is determined by the shift ratio, the side pressure on the pulleys, the belt speed, and the level of transmitted torque⁽⁹⁾. The number of repeated loads against fatigue life is known to be lower for the pulleys and elements than that for the rings⁽¹⁰⁾. For this reason, the reduction of impurities in the materials employed in the manufacture of the rings has been adopted as a method of increasing the fatigue strength of metal pushing V-belts⁽¹¹⁾.

However, the increasing requirement to expand the ratio range of CVTs and to employ them in combination with high-displacement engines makes it important to also study the fatigue strength of elements under torque amplification at CVT start-up. The strength of the rings has been increased by the enhancement of materials and application of heat treatments⁽¹²⁾, and because of this the elements, rather than the rings, have become the source of fractures in durability tests under high load conditions⁽¹³⁾. To enable a response to this situation, it is necessary to study the dynamic behavior of the metal pushing V-belt at CVT start-up and the stresses this generates on the elements.

The research discussed in this paper therefore set out to use simulations to quantify the stress history of the elements under transient operating conditions representative of CVT start-up, in order to clarify the level of strength of the metal pushing V-belt.

3. Element Stress Prediction Technology

A simulation technology that enables simultaneous simulation of the dynamic behavior of the belt and stress on the elements, which formed the subject of the previous report, was employed in this project to predict element stress at CVT start-up. This is the standard method of determining element stress, but when studying the dynamic strength of the rings in steady state operation, a considerable amount of calculation time is required in order to gradually increase the rotation of the pulleys from a stationary state to the speed employed in steady state operation. However, this project succeeded in reducing the calculation time to less than half that previously required, by dividing the analytical model of the belt into multiple computational domains to increase computational efficiency, and by focusing on the short period during which the CVT starts up from a state in which the pulleys are stationary.

3.1. FEM Model of Metal Pushing V-belt

The FEM model of the metal pushing V-belt employed in this research is shown in Fig. 3. Two deformable solid elements were used in the direction of thickness of each of the belt elements to enable bending deformation to be reproduced. In addition, the R section of the element neck, where stress is thought to concentrate, was divided into

three deformable solid elements.

However, the nose and hole sections were modeled using rigid elements, because the reproduction of detailed form was the priority in this case. By contrast, each ring layer was modeled using four deformable shell elements in the direction of width, in order to reproduce the crownings. In addition, contact surfaces were defined between the rings and the elements, between each element, between each ring, and between the elements and the pulleys, and appropriate friction characteristics were assigned to each.

3.2. Load Conditions at CVT Start-up

The torque input to the drive train can be divided into torque from the engine and torque from the wheels. Engine torque is considered to be the main torque input to the drive train, but the wheels have also been indicated as contributing a relatively high torque⁽¹⁴⁾. Care must be exercised in the case of CVTs equipped with torque converters, because the lack of a clutch mechanism on the driven pulley side prevents isolation from wheel torque. Figure 4 shows an example of measurements of changes over time in the load conditions on a metal pushing V-belt at CVT start-up. There is an immediate increase in pulley pressure when the throttle is completely opened, and the torque input to the metal pushing V-belt begins to increase as the pulleys begin to rotate. During this

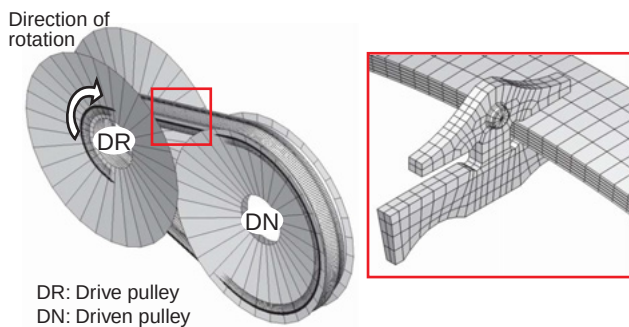


Fig. 3 Belt model defined as flexible bodies

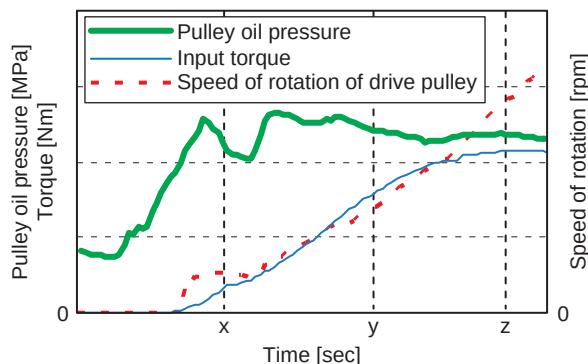


Fig. 4 Load conditions on CVT at start-up

period, the ratio remains LOW. The shorter the response time of the drive train to throttle operation, the more powerful the takeoff of the vehicle will be. Note that in this example it is engine torque that is input to the metal pushing V-belt.

3.3. Stress History of Elements at CVT Start-up

In an actual vehicle, the target ratio is maintained by feedback control of the side pressure on the pulley in which axial thrust is higher. In the simulation method used in this project, the side pressure on the drive and driven pulleys, the speed of the drive pulley, and the torque transmitted to the driven pulley are input as waveforms that change over time. A time history waveform of element stress obtained using this method is shown in Fig. 6. The dotted line shows the forward stress on the rear of the right side of the element neck, and the solid line shows the stress on the same position of the left side of the element neck (Fig. 5). Both waveforms show that maximum stress is generated immediately before the elements reach the exit of the drive pulley.

There is almost no difference in results for right and left, indicating that a symmetrical load acts on the right and left sides of the element neck. Figure 7 shows a comparison of the stress on the front and rear of an element in the direction of forward motion. Until the belt is approximately two-thirds of the distance around the

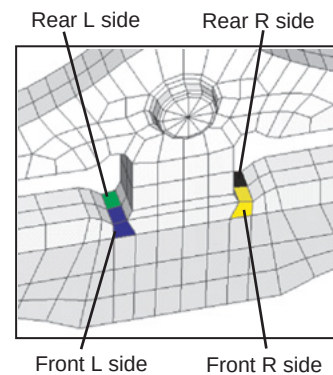


Fig. 5 Evaluation points for element stress

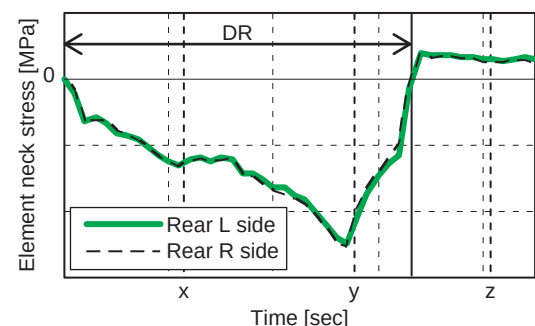


Fig. 6 Time history of element stress

drive pulley, both sides of the element neck are subjected to compression stress, and the absolute value of this stress is identical on both sides. After this, however, differences in the values begin to appear, and there is a change to the tensile stress present on the rear of the elements, immediately after the belt exits the drive pulley. This is considered to be because a pushing force between the elements, which is responsible for transmitting torque, begins to be generated when the elements are one-third of the distance from the pulley exit. The pushing force acts on the front and rear of the elements, but when the belt is wrapped around the drive pulley, it is higher on the front of the elements in the direction of forward motion (Fig. 8). Because of this, the elements display concave bending deformation in the direction of forward motion, and retain this deformation even after exiting the drive pulley (Fig. 9).

3.4. Distribution of Element Stress across the Entire Circumference of the Belt

The previous section focused on a single element, and determined a time history waveform of the stress on the element neck at CVT start-up. A time history waveform of element stress across the entire circumference of the belt can be obtained under steady-state operating conditions, but under the transient conditions of start-up, the elements have only moved a very small distance in

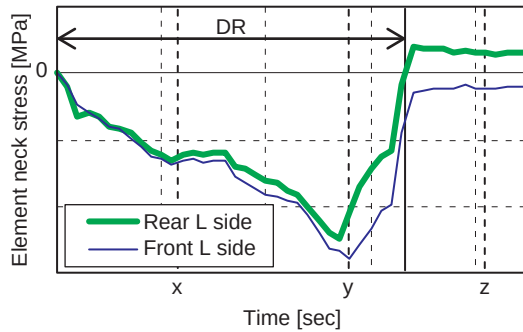


Fig. 7 Comparison of stress on front and rear of element

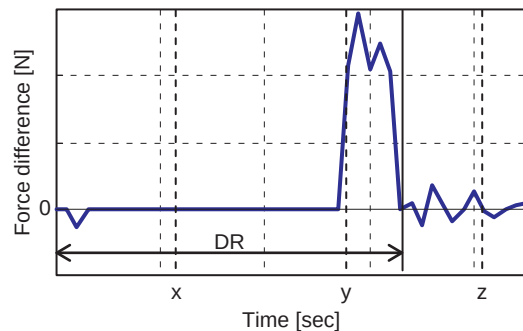
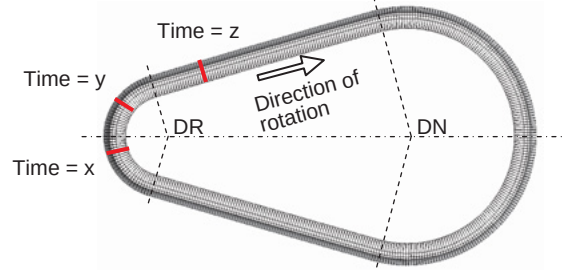


Fig. 8 Force difference between front and rear of element

relation to the entire belt. Because of this, obtaining the stress distribution of the elements across the entire belt represents a challenge. Figure 10 shows a contour diagram of the stress across the entire circumference of the belt at a specific time. Figure 11 shows the results of extracting the stress on the necks of all the elements. The times used here are x, y, and z in Fig. 4. The results shown in Fig. 11 indicate that the amplitude of stress on the necks is highest before and after the elements exit the drive pulley, and the figures demonstrate a good match with figures for the amplitude of stress in Fig. 7.



	Deformation	Stress distribution
Time = x		
Time = y		
Time = z		

Fig. 9 Deformation of element at start-up

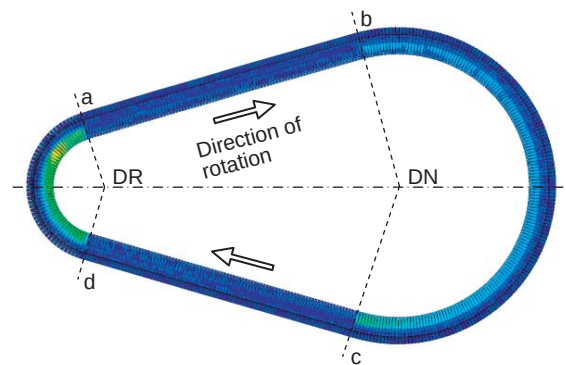


Fig. 10 Element stress distribution

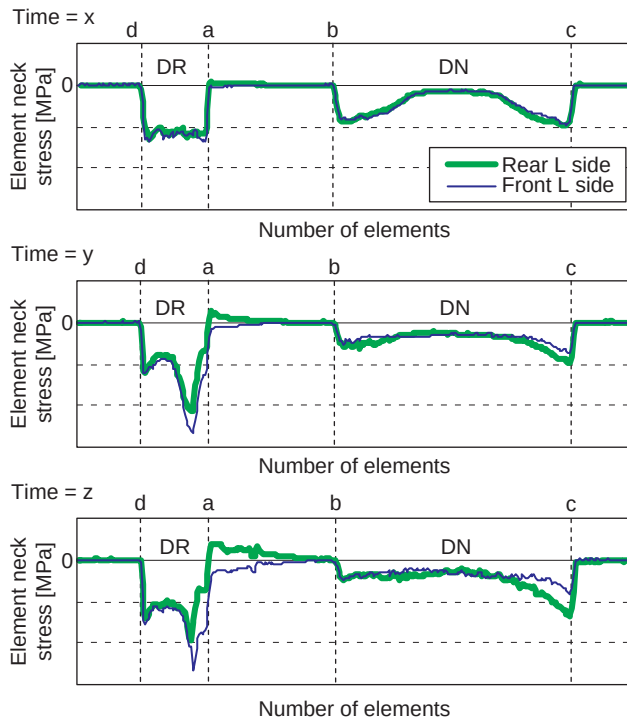


Fig. 11 Instantaneous stress distribution on element neck

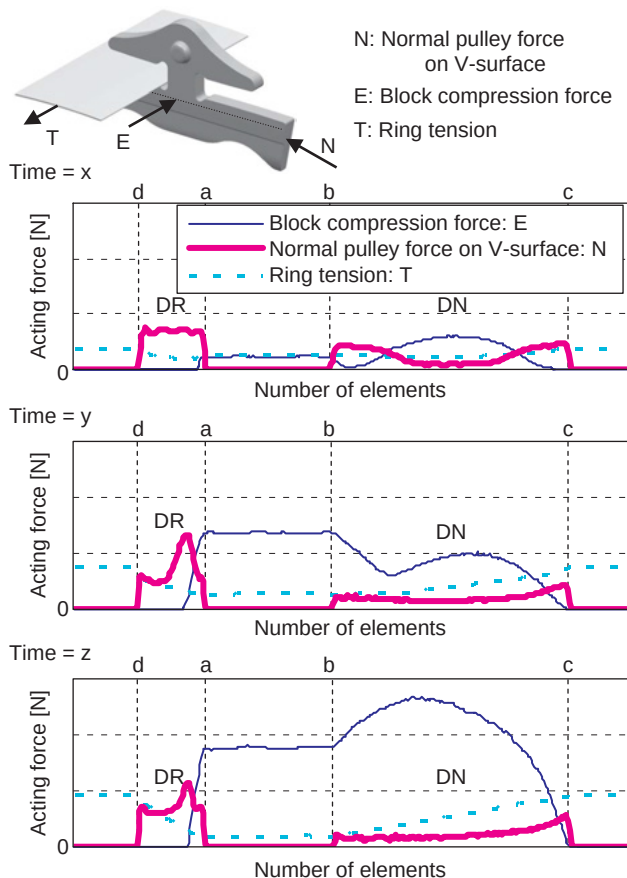


Fig. 12 Instantaneous acting forces across belt

3.5. Mechanism of Generation of Element Stress under Transient Operating Conditions

The torque transmission mechanism was next studied in order to clarify the dominant factors generating element stress. It is known that the torque transmitted by a metal pushing V-belt consists of a component transmitted by the pushing force between the belt elements, and a component transmitted by the difference in tensile force between the rings. Figure 12 shows the pushing force between the elements, the tensile force in the rings, and the distribution of load on the element V-surface under transient operating conditions at start-up. The block pushing force increases with time in section ab. The difference in tension between the rings also increases with time in sections cd and ab, and this contributes to torque transmission.

An examination of the distribution of load on the element V-surface reveals that it is similar to the distribution of element stress shown in Fig. 11. The results also show that element stress changes before and after the point at which the change in the pushing force between the elements is greatest. Given this, it is conjectured that the dominant factor in stress on the element necks is the load on the element V-surface, to which the bending caused by the pushing force between the elements is added.

4. Element Strength under Transient Operating Conditions

Using a vehicle to test the durability of the elements under transient operating conditions would be impractical due to the enormous amount of test time required to repeat the starting and stopping of the CVT. The present project therefore employed durability tests under steady-state operating conditions, with throttle opening as a parameter.

4.1. Element Stress under Steady-state Operating Conditions

Figure 13 shows the stress waveform for the element necks under specific steady-state operating conditions obtained from a simulation.

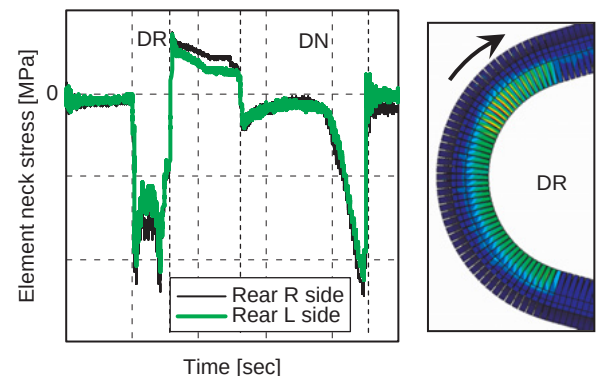


Fig. 13 Element stress in steady-state

4.2. Validation of Element Stress Results

In order to confirm the validity of the figures for element stress obtained from the simulation, they were compared with figures for loads acting on the elements

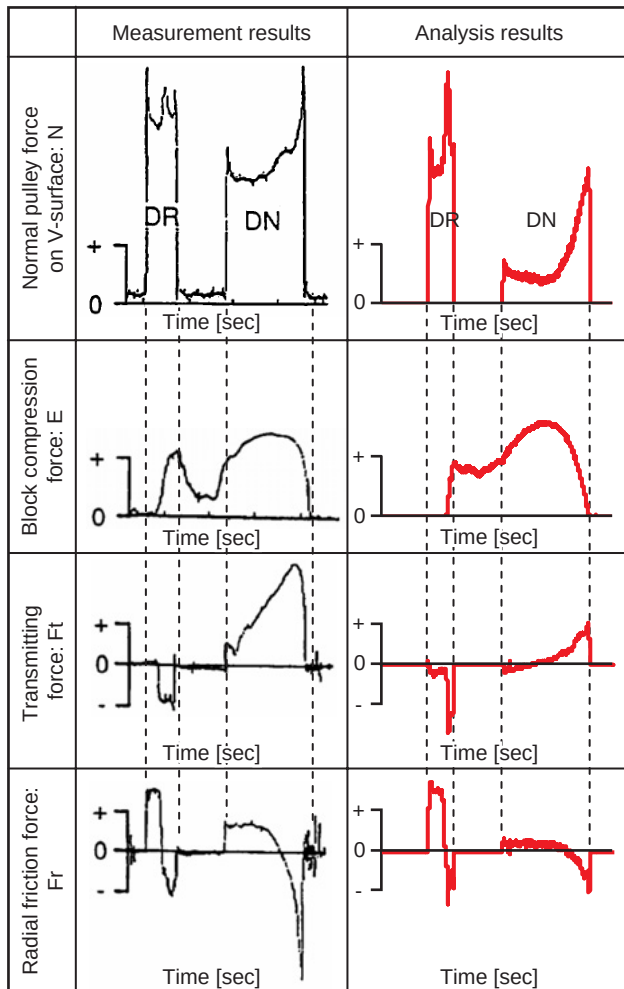
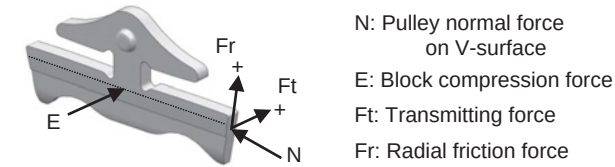


Fig. 14 Comparison of acting forces on element

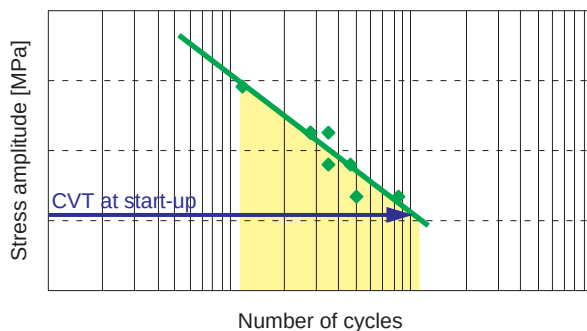


Fig. 15 Stress number diagram

during one revolution of the belt obtained from tests. The elements were additionally machined to increase the sensitivity of test results for loads in specific directions⁽¹⁵⁾. This made it unable to verify the figures quantitatively, but there was a reliable qualitative correlation between the load distribution in the simulation results and the test results (Fig. 14).

4.3. Level of Belt Strength under Transient Operating Conditions

Figure 15 shows an S-N diagram for the belt, obtained from the results of steady-state durability tests conducted using a LOW ratio under four different load conditions. The vertical axis shows the amplitude of stress on the element necks obtained from the simulation under steady-state operating conditions. The results indicate that there is a correlation between element strength and the amplitude of stress on the necks of the elements. The stress amplitudes from Fig. 11 were superimposed on the S-N diagram as a horizontal line to enable the positioning of the strength of the elements under transient operating conditions to be determined. The point at which the S-N diagram and the horizontal line intersect indicates that the conditions of the present durability test include transient conditions of the type occurring at CVT start-up, and confirm that the metal pushing V-belt possesses sufficient dynamic strength under these conditions.

5. Conclusion

The following results were obtained by applying a technology enabling prediction of element stress in a metal pushing V-belt to transient operating conditions:

- (1) At CVT start-up, the maximum stress amplitude on the element necks is generated before and after the drive pulley exit.
- (2) The load on the element V-surfaces is considered to be the dominant factor in stress on the element necks, to which bending deformation caused by the pushing force between the elements is added.
- (3) An S-N diagram for the neck section of the elements was formulated from the results of simulations and durability tests conducted under steady-state conditions, and the level of strength of the metal pushing V-belt under transient conditions was clarified. This indicates that the method used in this project can also be successfully employed to study the dynamic strength of metal pushing V-belts under transient operating conditions.

6. Afterword

The requirement to increase the transmission capacity of the metal pushing V-belts employed in CVT is today increasing rapidly. The research discussed in this paper has indicated that a simulation can be used to shed light on the stress history of a belt element under transient

operating conditions. It is expected that the accuracy of this method will be increased in the future, and that it will be used to assist in the development of highly responsive high-capacity CVTs.

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