

# Development of Simulation Technique for Element Stress Prediction of Metal Pushing V-belt

Toshihiro SAITO\*

Koji MIYAMOTO\*\*

## ABSTRACT

A simulation method enabling simultaneous prediction of dynamic behavior and stress distribution on element has been developed for durability evaluation of dynamic strength of metal pushing V-belts. The finite-element-method that enables contact analyses in time history with large-scale model was adopted to reproduce the dynamic behavior of the V-belt in high rotational speed range of CVT. This paper focuses on the element strength in actual operation of CVT, and also discusses modifications made to the previously reported simulation method to enable the prediction of detailed stress. A new technique named inertia-relief is introduced needless of applying the constraint conditions when calculating the detailed stress on element in respectively. This results in allowing the stress distribution on any element to be found at any position on the trajectory of the V-belt. Using this technique, it has been found that the stress on the necks of elements at the entrance and exit of the pulleys affects the dynamic strength of the V-belt. Furthermore, a method of evaluating this stress was also determined. In addition, consideration was given to the effect of the elements tail side concave shape on the dynamic strength of the V-belt.

## 1. Introduction

Against a background of rising demands for responses to environmental issues, automotive manufacturers are directing attention towards CVTs as a technology enabling the achievement of a balance between driving performance and fuel economy. In terms of driving performance, CVTs offer quietness and smooth acceleration without shift shock. From the perspective of fuel economy, cooperative control between the CVT and the engine enables engine speed to maintain the high combustion efficiency, resulting in a higher level of fuel economy than is available from an AT. Therefore, the needs for increases in transmitting capacity of CVTs will become greater<sup>(1), (2)</sup>. The important factor in attempting to increase transmitting capacity is ensuring the dynamic

strength of the metal pushing V-belt. Dynamic strength cannot be determined simply from the maximum input torque, but must be determined experimentally in relation to the shift ratio, pulley piston pressure as well as the maximum rated speed. This is because it is generally difficult to measure element stress, a factor which is indispensable in determining the strength of the belt in actual CVT operation<sup>(3), (4)</sup>. It is therefore both technically and procedurally difficult to optimize the shape of the belt for higher-speed operation, making it necessary to develop a theoretical method of determining the effect of the shape of the belt, and in particular the shape of the elements, on dynamic strength<sup>(5)</sup>. A previous study<sup>(3)</sup> by one of the present authors focused on dynamic stress on the multi-layered rings in actual operation of the belt, and developed a technique for simulating belt behavior. The effect of the deflection rigidity of

\* Tochigi R&amp;D Center

\*\* ITO CORP.

the pulley on ring stress has also been studied<sup>(6)</sup>. This paper discusses the development of a method of calculating the detailed stress on individual elements using element contact pressure obtained from the belt behavior simulation mentioned above. This has made it possible for the first time to determine the stress on elements at any point on the circumference of the belt in the high rotational speed range. This paper will clarify the effect of element neck stress on the dynamic strength of the belt when the metal pushing V-belt is close to the entrances and exits of the pulleys.

## 2. Development Goals

Figure 1 shows a cutaway view of the main section of a CVT, and Fig. 2 shows a metal pushing V-belt manufactured originally. Drive torque is transmitted from the drive pulley to the driven pulley, by means of friction between the elements and the pulleys.

This friction is generated by there being pulley piston pressure constricting the belt. The stress on the elements and rings during vehicle operation is determined by the following factors: shift ratio, pulley piston pressure, engine speed and level of torque transmitted<sup>(7)</sup>. Tests have shown that the fatigue load of the pulleys and elements is lower than that of the rings<sup>(8)</sup>, and therefore reduction of impurities in the ring materials, to increase fatigue strength, has been adopted as a method of increasing the overall dynamic strength of the belt<sup>(9)</sup>.

Given the increasing requirements for expanding the ratio range of CVTs and employing them in combination with high-speed engines, determining the fatigue strength of the elements acted on

by centrifugal force is becoming more important. Modifications of materials have resulted in an increase in the fatigue strength of the rings<sup>(10)</sup>, where now the elements rather than the rings have become the points of failure in high-speed durability tests<sup>(11)</sup> (Fig. 3). It is essential to understand the behavior of the elements and the stresses produced on them when the belt is in operation to address this issue. Therefore, the research discussed in this paper attempts to develop a technique to enable prediction of the element stress, in order to clarify the mechanism of failure of the elements in high-speed operation.

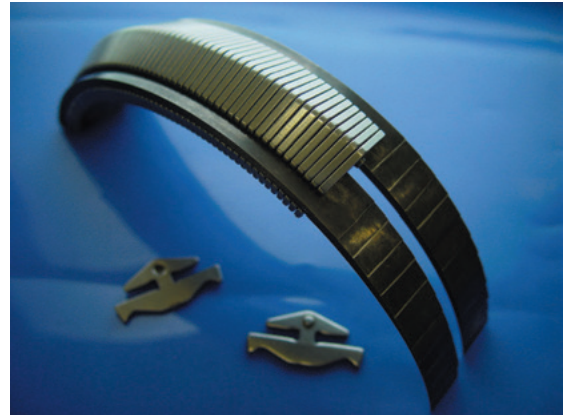


Fig. 2 Metal pushing V-belt

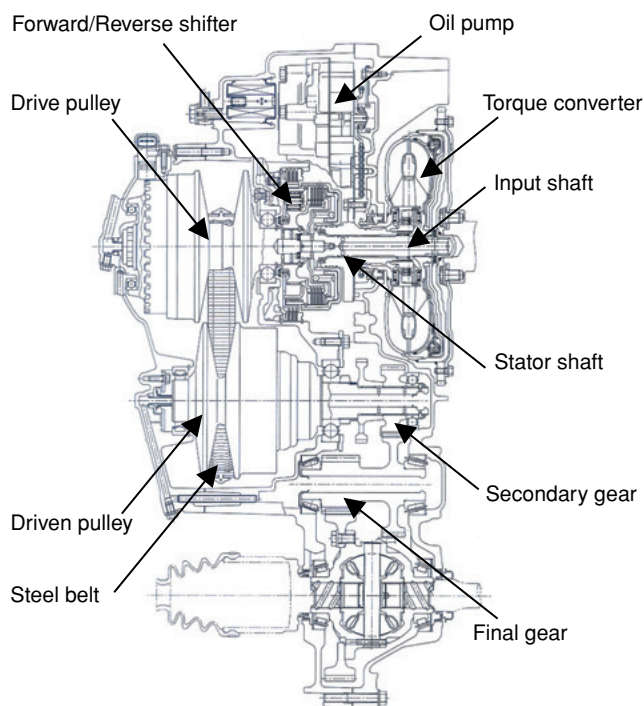


Fig. 1 CVT main section



Fig. 3 Damaged element

## 3. Technique for Element Stress Prediction

The simulation method used in this project is the standard method for predicting element stress, but too much calculation time was required when focusing on the dynamic stress on the multilayered rings<sup>(6)</sup>. However, employing parallel computation, using the latest domain decomposition, enabled calculations to be conducted in approximately the same time as that required for durability testing.

### 3.1. FEM Model of Metal Pushing V-belt

Figure 4 shows an FEM model of our original metal pushing V-belt. Two deformable solid elements are employed in the direction of thickness for individual elements to reproduce bending deformation. Three deformable solid elements are used to divide the R section of the element neck, where stress is thought to concentrate. Reproduction of detailed form of the nose and hole sections has been prioritized, and therefore modeled with rigid

elements. Four deformable shell elements have been used in the direction of width to model each layer of rings to enable reproduction of the crowning of the rings. In addition, the ring-element, element-element, ring-ring and element-pulley contact surfaces have been defined, and appropriate friction characteristics have been assigned in each case.

### 3.2. Pulley Rigid Surface Model

Pulley rigidity has a tremendous influence on the dynamic behavior of the belt, and connector elements were therefore used to reproduce deflection rigidity. Different rigidity values were assigned to the pulley that moves in the axial direction, and to the fixed shaft pulley. The rigidity values were reverse-calculated from figures for flexion obtained from applying a static belt load and pulley piston pressure to a 3D FEM pulley model. However, the pulley surfaces are defined as rigid surfaces. If they were modeled with deformable solid elements, it would be unlikely to reproduce the smooth surfaces of the pulleys.

### 3.3. Belt Misalignment

As it wraps around the drive and driven pulleys, the center of the belt does not move within a single plane, but displays slight deviations outside the plane. This deviation of the belt from the plane is termed misalignment. Durability tests have shown that a large misalignment reduces the lifespan of the belt. However, even if the pulleys were defined as rigid bodies, misalignment would not be eliminated; the size of the misalignment is determined by the distance between the axes of the pulleys and the shift ratio. A full 3D model rather than a plane symmetry model was therefore used in the simulation.

### 3.4. Analytic Procedure

Figure 5 shows the steps used in analyses employing the belt behavioral simulation. Finite element codes, which enable large-scale contact analyses over a time history were employed in the simulation. With the belt in its initial, no stress, and perfectly circular state, the pulleys are moved a fixed distance to produce a transmission ratio. Next, misalignment is imparted to one pulley

and pulley piston pressure is applied, as the drive pulley is gradually forced to rotate until the target speed is reached. During this procedure, counter-torque, representing the engine input torque multiplied by the shift ratio, is gradually applied to the driven pulley. This continues until rotation speed, pulley piston pressure and torque are judged to be steady.

### 3.5. Accuracy of Simulated System

In actual operation, feedback control of the pulley piston pressure of the pulley around which the largest diameter of the belt is wrapped is used to maintain the target ratio<sup>(12)</sup>. Because the pulley piston pressure is constant in the simulation, the shift ratio and the rotational speed of the driven pulley respond as a system. A time history of the response indicates the accuracy of the simulated system. As Fig. 6 shows, the target ratio is maintained when load conditions become stable.

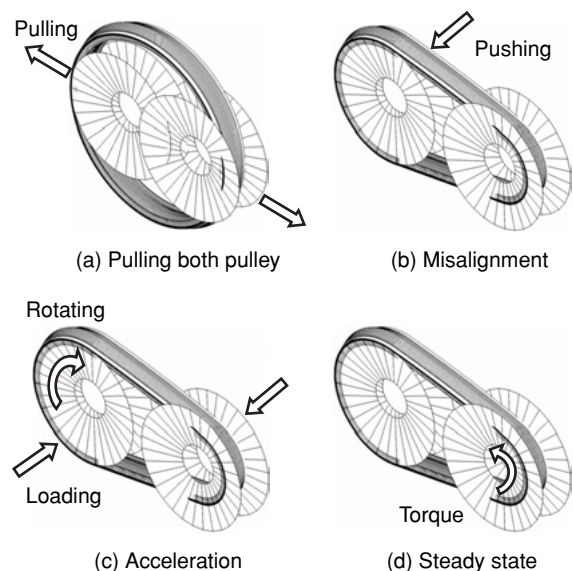


Fig. 5 Analysis procedure

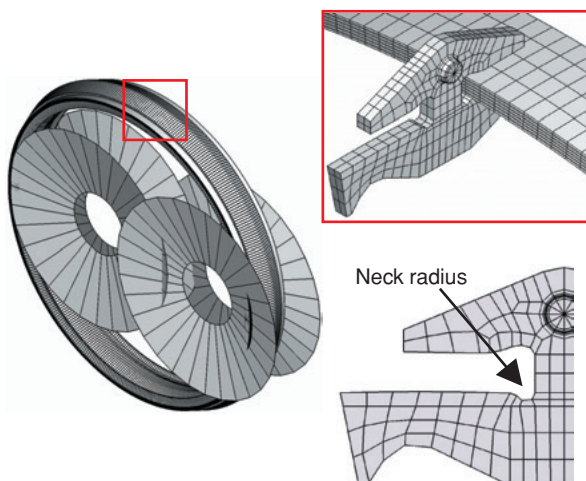


Fig. 4 Belt model defined as deformable bodies

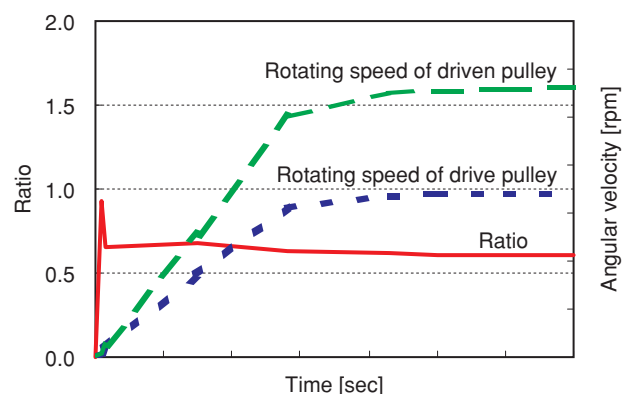


Fig. 6 Time history of ratio

### 3.6. Element Stress during Actual Belt Operation

Figure 7 shows a contour diagram of the stress on the elements in this simulation when the belt is rotating at a constant speed. The compression stress near the locking edges, the main cause of which is believed to be the pushing force between the elements, increases from the drive pulley entrance, reaches its peak close to the drive pulley exit, then disappears at the driven pulley exit. The stress on the element necks, the assumed point of failure of the elements, is highest as the belt approaches the entrances and exits of the pulleys. The stress generated by the pushing force is at its highest at the exit of the drive pulley. This is believed to be because of the reaction force generated on the element V surfaces at the instant the belt enters and exits the pulleys, as shown in Fig. 8<sup>(13)</sup>.

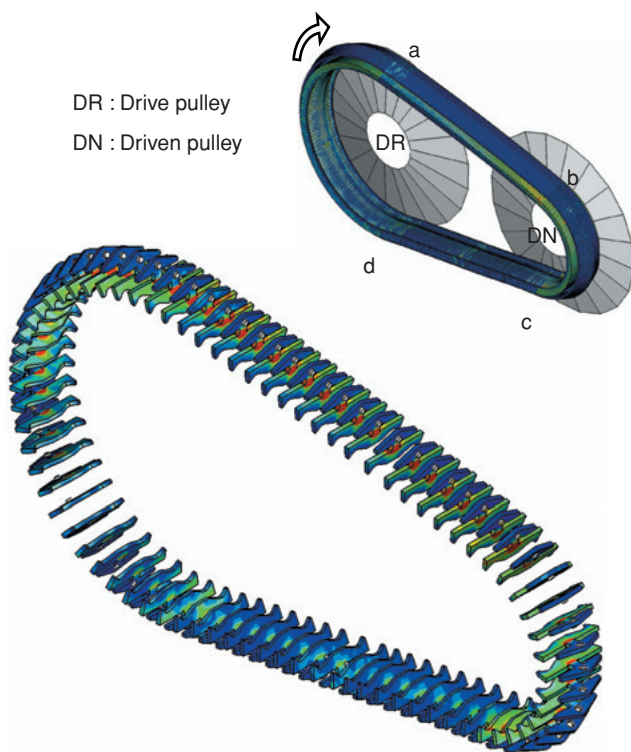


Fig. 7 Element stress distribution

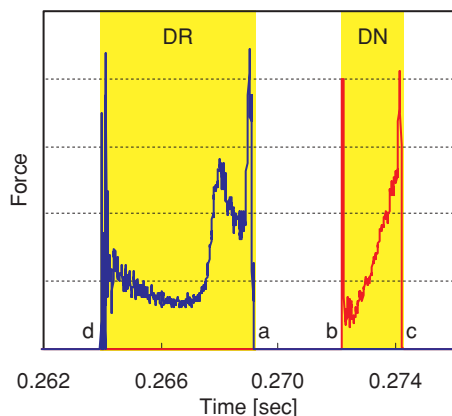


Fig. 8 Reaction force on V-surface

## 4. Development of Technique for Prediction of Detailed Stress on Elements

As indicated at the beginning of the previous chapter, the calculation time required makes it impractical to use a stress simulation in which all the elements are defined as deformable bodies in the development process for metal pushing V-belts. It was therefore decided to use results from the previously mentioned belt behavior simulation, in which the elements are defined as rigid bodies, to simulate element stress.

### 4.1. Inertia Relief Method

The detailed stress on the elements was found from this belt simulation model, and the distribution of the contact pressure acting on the elements was determined. This contact pressure was applied to a finely subdivided deformable element model of an individual CVT element. Normally, it would be unlikely to conduct a static stress analysis without applying constraint conditions at several nodes of the element model and stopping operation as a rigid body. However, when constraint conditions are applied, stress concentrates around the points of constraint, causing the originally deformed section to become fixed and preventing the achievement of an accurate stress distribution. A method of static stress analysis known as inertia relief was therefore employed. In this method, the inertia of residual forces is automatically applied to the center of gravity, in order to balance the element to which surface pressure is applied in space. This enables static stress analysis without the requirement for constraint conditions.

### 4.2. Distribution of Detailed Stress on Elements

Figure 9 shows the distribution of detailed stress on elements obtained using this method. This example shows elements approaching the entrance and exit of a pulley on the trajectory of the V-belt (Fig. 7). The results of stress analysis using the belt

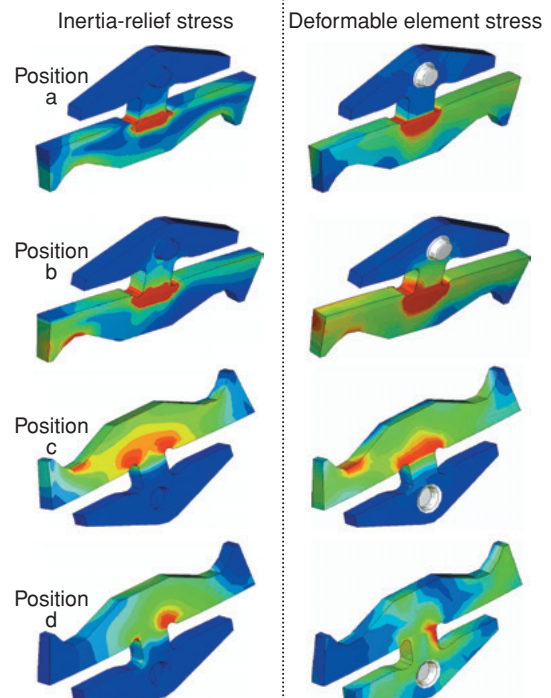


Fig. 9 Stress comparison at each position

behavioral model in which the elements are defined as deformable bodies are also shown. There are slight differences between the two sets of results, but they reproduce a basically similar stress distribution.

## 5. Element Strength in the High Rotational Speed Range

### 5.1. Engine Speed and Element Stress

Figure 10 shows the detailed stress on an element in the high rotational speed range. Element stress increases dramatically as

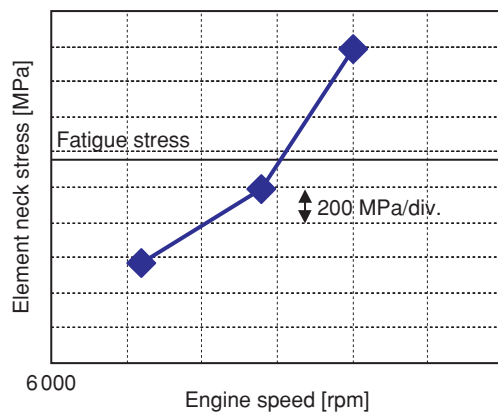


Fig. 10 Element neck stress influenced by engine speed

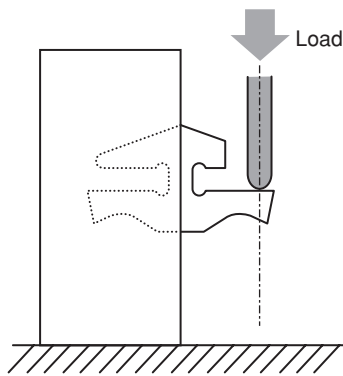


Fig. 11 Schematic of element fatigue test

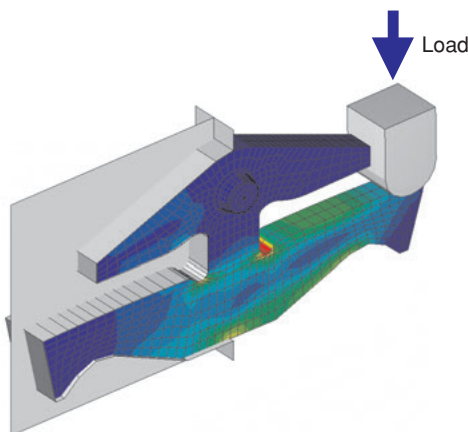


Fig. 12 Element fatigue stress

engine speed increases. This plot is for the maximum stress, generated at the entrances and exits of the pulley. Focus was placed on the base of the neck, R, of the element. In durability tests conducted under the same operating conditions, the belt comes closer to the limit of its dynamic strength as the speed of rotation increased. Simulation results for element stress showed a good correlation with test results.

### 5.2. Fatigue Strength of Individual Elements

Next, fatigue tests were conducted on individual elements to determine the accuracy of the stress on the elements in operation. Figure 11 shows the element fatigue test apparatus. In the tests, half of the element is inserted into a mold to fix it in position, and a sine load is applied to the tip of the element edge. This test enables the fatigue limit load to be ascertained<sup>(11)</sup>.

Fatigue limit stress was determined using the analysis model shown in Fig. 12. The same finite element model was employed in this analysis as was that used in the analysis of detailed stress with inertia relief. The fatigue limit stress values determined from the element test correlated well with the results of durability tests, indicating its usefulness as a benchmark for quantitative judgment of the element stress when the belt is in operation.

## 6. Application to Metal Pushing V-belt Development

Element strength can be increased in a number of ways. Just as ring strength can be increased by attention to materials, heat treatment and shot peening can be applied to the elements to increase their surface hardness. However, the issue under consideration in this paper is the influence of the shape of the elements on the dynamic strength of the belt.

As Fig. 8 shows, the load on the element V-surface becomes a reaction force at the entrance and exit of the pulleys. This reaction force is closely related to the deflection rigidity of the pulleys. A previous study has demonstrated that reducing deflection rigidity reduces the reaction force on the elements, resulting in increased dynamic strength. The project therefore considered an element shape that would reduce the reaction force. As Fig. 13 shows, a concavity was added to the tail of the elements to reduce the area of contact between them.

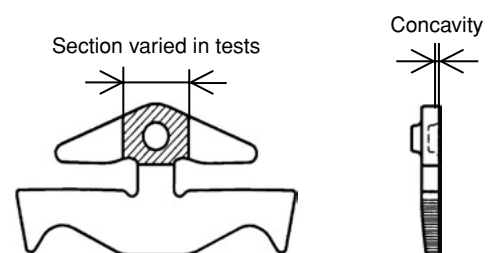


Fig. 13 Concave shape for control of contact area between elements

Elements with concave areas of differing widths were modeled and labeled X, Y and Z in descending order of width. Figure 14 shows results obtained from conducting the belt behavior simulation using these elements. The graphs show that the V-surface reaction force varies with the width of the concavity of the element. Focusing on the load peak at the abovementioned exit of the drive pulley shows that reaction force does not vary uniformly with changes in the width of the concavity, but that a minimum value exists. In durability tests of belts with elements of varying concavities, belt life increased as the V-surface reaction force peaks decreased. Case Y, which produced the lowest load peaks in the simulation, ensured the dynamic strength of the belt in high-speed operation, verifying the effectiveness of the method discussed in this paper. This phenomenon cannot be explained solely in terms of the rigidity of the elements; it can be explained only after element behavior and load have been identified.

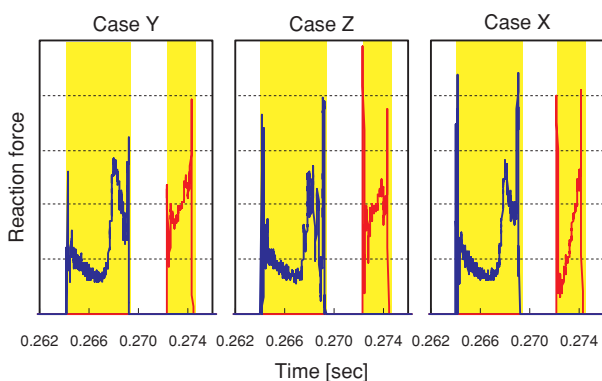


Fig. 14 Reaction forces on V-surface for each case

## 7. Conclusion

The following techniques were developed to study the dynamic strength of metal pushing V-belts in operation:

- (1) A static analysis technique that combined the inertia relief method and contact pressure drawn from a belt behavior simulation using rigid elements was developed.
- (2) This allowed the detailed stress on any element to be determined at any position on the trajectory of the V-belt.
- (3) Stress distribution determined using this method showed good correlation with the results of a belt behavior simulation using deformable elements.

The following results were obtained using the new technique:

- (1) The stress on the neck of the element, which is presumed to be the point of failure, is highest close to the entrances and the exits of the pulleys. This is because of the reaction force generated at the instant the belt enters and exits the pulleys.
- (2) At high rotational speeds, element stress rapidly increases, bringing the elements closer to their strength limits. Data on fatigue limit stress obtained from individual element tests provides a benchmark for judgment of element strength in actual operation.
- (3) Optimization of a concavity at the tail of the elements increased the dynamic strength of the belt in the high rotational speed range.

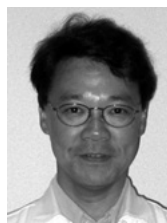
## 8. Afterword

Increasing the transmitting capacity of metal pushing V-belts has rapidly become a significant requirement in the automotive industry. The complexity of the subject makes a theoretical approach to be a challenge, and the authors hope that they can enhance analytic techniques to contribute to this field.

## References

- (1) Sato, Y., Urano, J., Ohashi, A., Sakuma, S., Yamaguchi, M.: Development of CVT for 2004 Model Odyssey, Honda R&D Technical Review, Vol. 16, No. 2, p. 87-94
- (2) Kato, Y., et al.: A Study on the Torque Capacity of Belt CVTs for 2.0-liter and 3.5-liter Front-Drive Cars, JSAE Autumn Convention, No. 65-03, p. 1-4 (2003)
- (3) Saito, T., Okano, T.: Development of Metal Pushing V-Belt Stress Simulation for Continuously Variable Transmission, Honda R&D Technical Review, Vol. 13, No. 1, p. 125-130
- (4) Shimizu, H., et al.: Development of 3-D Simulation for Analyzing the Dynamic Behavior of a Metal Pushing V-Belt for CVTs, JSAE Spring Convention, No. 8-99, p. 9-12 (1999)
- (5) Fujita, M., et al.: Development of 3-D simulation for power transmitting analysis of CVT driven by dry hybrid V-belt, San Francisco, VDI-Verlag (2004)
- (6) Saito, T., Okano, T.: Application of Metal Pushing V-Belt Stress Simulation with CVT pulley stiffness, Honda R&D Technical Review, Vol. 14, No. 1, p. 191-196
- (7) Kanehara, S., Fujii, T.: A Study on Power Transmitting Mechanism of Metal Pushing V-Belt, HONDA R&D Technical Review, Vol. 7, p. 49-67
- (8) Pennings, B., et al.: New Push-Belt Design to Increase Power Density of CVTs Featuring a New Maraging Steel, San Francisco, VDI-Verlag (2004)
- (9) Yagasaki, T., Aoyama, H., Saito, T., Ishii, K., Okada, Y., Arikawa, M.: Development of Metal Pushing V-Belt for Continuously Variable Transmission, Honda R&D Technical Review, Vol. 14, No. 1, p. 181-190
- (10) Sluis, V. D., et al.: Stress reduction in push belt rings using residual stresses, Proceedings of CVT2002 Congress, VDI-Berichte 1709, Munich, p. 383-402 (2002)
- (11) Yagasaki, T., Aoyama, H., Ohnuki, M., Okada, Y., Kataoka, R.: Development of Metal Pushing V-Belt for Continuously Variable Transmission for 2L Class Vehicle, Honda R&D Technical Review, Vol. 16, No. 2, p. 95-102
- (12) Saito, T., et al.: Development of a Simulation Technique for CVT Metal Pushing V-belt with Feedback Control, SAE Paper, 2004-01-1326
- (13) Sauer, G.: Grundlagen und Betriebsverhalten eines Zugketten Umschlingungsgetriebes, Nr. 293, Dusseldorf, VDI-Verlag (1996)

■ Authors ■



Toshihiro SAITO



Koji MIYAMOTO