

Development of Metal Pushing V-Belt Stress Simulation for Continuously Variable Transmission

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ABSTRACT

This paper describes the development of a new method to evaluate dynamic behavior and stress for durability simulations of metal pushing CVT V-belts undergoing high rotational speeds. The explicit finite element method typically used in crash analysis is adopted to simulate the high rotational speed range. A finite element model of the complete metal pushing V-belt including the layered bands is constructed where the torque is transmitted by the friction of the contact surface. In the simulation, the rotational speed gradually increases from zero to the target speed. As a result, it is possible to predict the belt stress in the high speed range and as this stress correlated with the test results, belt durability can, for the first time, be judged. To make this simulation more accessible to designers, customized pre- and post-analyzing tools were developed that enable the quick creation of new belt models.

1. Introduction

As demands for environmentally conscious automobiles have grown over the years, various companies have focused on the continuously variable transmission (CVT) as a transmission technology that can simultaneously achieve performance and fuel economy. CVT performance is characterized by quietness, smooth acceleration without shift shocks, and fuel economy superior to that of automatic transmissions achieved by maintaining a rotational speed range with high combustion efficiency through integrated control with the engine. Therefore, as the need for expanded transmission capacity continues to increase for the CVT, it is essential that the durability of the metal belt that forms the framework of the system be increased. Further, the demanded maximum rotational speed is also increasing. However, the transmission mechanism of metal belts is based on contact and friction transmission, so an analytical approach is difficult and vast amounts of development man-hours have been devoted to repeated test confirmation.⁽¹⁾

This paper first describes the development of a simulation method that is capable of predicting metal belt behavior and stress near the maximum rotational speed, and that the strength can be determined from a durability SN curve. Customized pre- and post-processing tools have also been developed so that this technology can be widely used by designers, and these details are also reported.

2. Development Aims

Fig. 1 shows the main section of the CVT used in this development. As shown in this figure, the driving torque is shifted and transmitted by a metal belt from the driving pulley to the driven pulley. In addition, the CVT mechanism shifts the ratio by moving a pair of opposing movable pulleys in the axial direction, so there is some misalignment that cannot be canceled, and the amplitude of this misalignment is

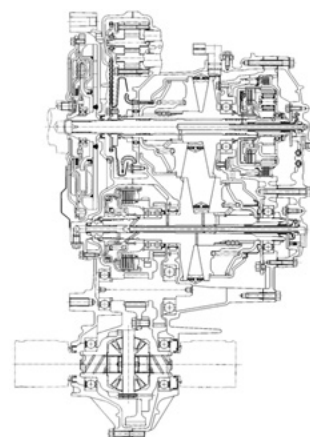


Fig. 1 CVT main section

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determined by the distance between pulley axles and the operating ratio.

The metal belt used was made by Van Doornes Transmission Inc., and was comprised of approximately 428 elements and two rows of 12 rings. (See Fig. 2.) Each ring layer exhibits relative sliding behavior at ratios other than 1.0, and the innermost ring also exhibits relative sliding between elements. The origin of failures at high rotational speeds is presumed to be the inner surface of the innermost rings.



Fig. 2 Metal pushing V-belt

Based on these characteristics, the development aims were set as follows:

- (1) calculating the stress of the innermost ring at the maximum rotational speed;
- (2) creating an SN diagram during high-speed durability testing;
- (3) investigating the influence of pulley rigidity on belt durability; and,
- (4) developing simulation technology that is easy to use.

3. Simulation Development

3.1 Selection of a solver

Metal belts transmit torque by the compressive force between the elements and the tensile force difference of the rings.⁽²⁾ This tensile force difference is produced by the friction force between the rings and the elements mandating that the relative behavior of these components be accurately determined. All metal belt components must be precisely modeled in order to determine the stress of the innermost ring. This modeling method must also take into account the movement and behavior of the individual elements and the ring layers.

The solver employed as the solution method that meets these demands is a general-purpose non-linear finite element method which is classified as a crash analysis code. Most crash analysis codes emphasize calculation efficiency when solving dynamic contact problems. However, a solver with a kinematics contact that does not sacrifice calculation accuracy, even in a kinematics sense, was adopted.

3.2 Simulation method

Fig. 3 shows the metal belt model in the condition prior to analysis. Each ring layer is defined as an elastic body, and the elements are treated as rigid bodies in order to place emphasis on reproducing the detailed shape. The pulley model should normally be treated as an elastic body, but a rigid body was used to reduce the calculation time.

In addition, the perfectly circular shape prior to analysis was used as the zero stress condition for the metal belt.

The analytic process was set up as if actually mounting a metal belt on a CVT and operating the engine. First, the distance between pulley axles is adjusted. Then the belt is clamped by the driving and driven pulley side pressure and the driving pulley is accelerated to the limit rotational speed in a manner so as to prevent belt slipping. Next, all operating conditions are held constant and the calculation process is complete at the point when the ring stress reaches steady state. This method requires a lot of time for analysis, but is considered necessary in order to accurately reproduce the irreversibility of contact and friction.⁽³⁾⁽⁴⁾ (See Fig. 4.)

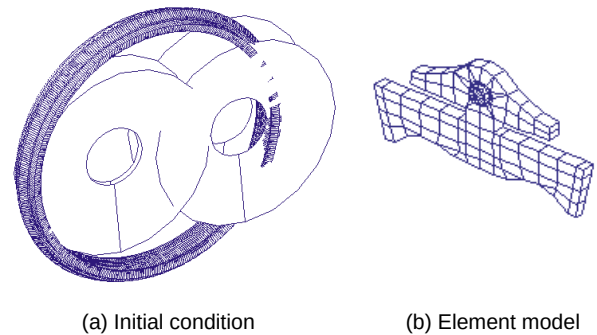


Fig. 3 Metal pushing V-belt model

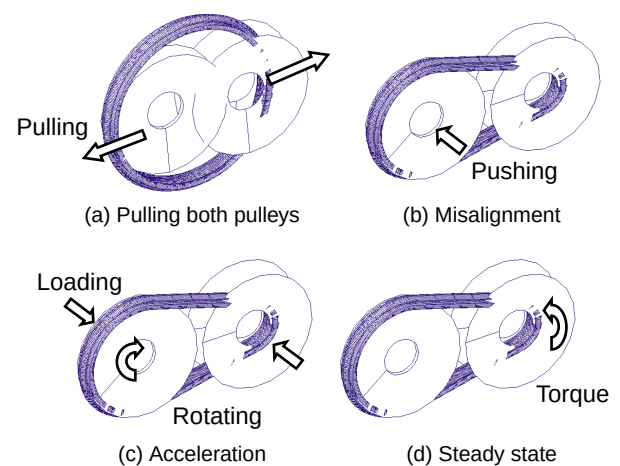


Fig. 4 Analysis procedure

In addition, Fig. 5 shows the relationship between the simulation input conditions and output results. Of these variables, the parameter for the coefficient of friction at each contact surface must be determined through correlation with the measurement results.

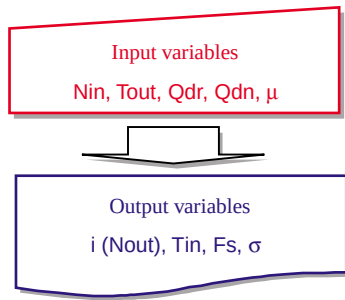


Fig. 5 Input and output variables of analysis

3.3 Verification of accuracy

Fig. 6 shows a comparison of the results obtained by this simulation method and measurement results in order to verify the accuracy. The measurements used a metal belt with only one layer of rings. The figure shows the signal from a strain gauge affixed to the outer circumference of the rings.⁽⁵⁾ The measurement conditions were 1000 rpm and no torque load. These results show that the ring stress is accurately reproduced, and these coefficients of friction at each part were used without modification in simulations at the maximum rotational speed.⁽⁶⁾

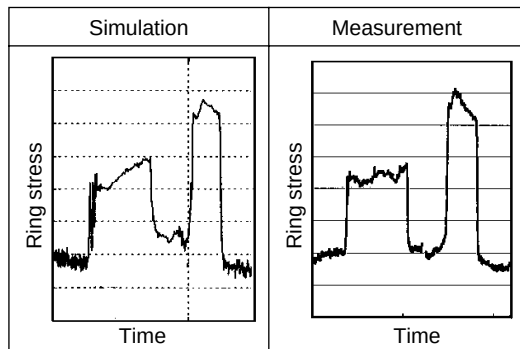


Fig. 6 Comparison of results

3.4 Innermost ring stress

Fig. 7 shows a time history waveform of the innermost ring stress when this simulation method is applied to CVT operating conditions at the maximum rotational speed. The calculation conditions were an engine rotational speed of 6000 rpm, a ratio of 0.61, and transmission torque of 143 Nm.

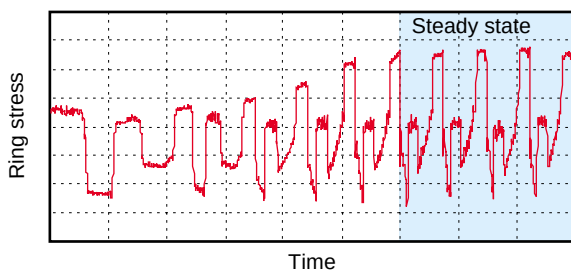


Fig. 7 Time history of ring stress

As shown by this stress waveform, when the operating conditions reach a steady state, the stress waveform also repeats nearly the same waveform, which indicates that a steady state can be reproduced at the maximum rotational speed.

In addition, this simulation method also takes into account belt misalignment. A difference can be seen between the left and right ring stress waveform. (See Fig. 8.) The rings have a crown shape to suppress sliding to the sides between ring layers caused by misalignment, and a stress distribution is produced across the rings when a tensile load is applied. Misalignment was found to further promote this stress distribution and to increase the stress on the edges of the rings.

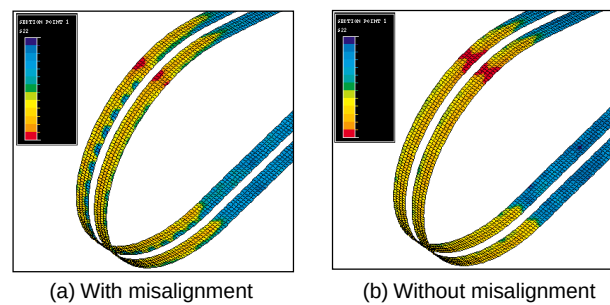


Fig. 8 Influence of belt misalignment

4. Belt Durability Judgement

The CVT operating conditions are prescribed by the ratio, transmission torque, engine rotational speed and both pulley side pressures. That is to say, each of these parameters influences the ring stress waveform, and it is important to operate in a stress state that does not exceed the ring fatigue life.

4.1 SN diagram during high-speed durability testing

Therefore, the ratio was fixed, and two levels were selected for the transmission torque, engine rotational speed and pulley side pressure. Then, the belt life to failure was measured in order to investigate belt durability near the maximum rotational speed. In all cases the cause of failure was assumed to be fatigue failure originating at the inner surface of the innermost ring.

This simulation method was applied to obtain the innermost ring stress corresponding to these operating conditions. Fig. 9 shows the resulting SN diagram during the high-speed durability test. The correlation coefficient of 0.92, indicated a high degree of correlation.

The above results indicated for the first time that belt durability near the maximum rotational speed can be judged according to the stress amplitude on the inside of the innermost ring.

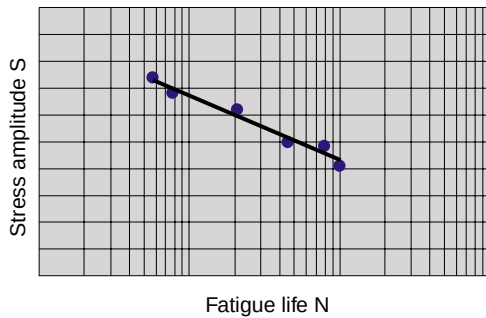


Fig. 9 V-belt SN curve

5. Enhancing Belt Durability

The most effective method for enhancing belt durability is to investigate the influence of the metal belt specifications on the ring stress. However, as previously mentioned the metal belt used was made by Van Doornes Transmission Inc., and it would be difficult to change the specifications. Therefore, the decision was made to examine pulley rigidity, which has a direct influence on belt behavior.

5.1 Influence of pulley rigidity

Fig. 10 shows the analysis model used to investigate the influence of pulley rigidity. The driving side and driven side were both modeled as movable pulleys, with equivalent rigidity. Symmetrical conditions are used to shorten the calculation time, with belt misalignment not taken into account. In other words, only the influence of the pulley deflection on belt stress was investigated.

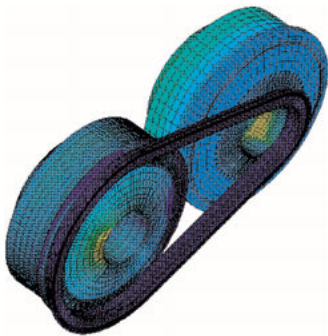


Fig. 10 Flexible pulley model

In addition, Fig. 11 shows the amount of pulley deflection when this simulation method is applied in terms of tip displacement.

Pulley deflection increases toward the tip, being greater for the driving side which turns the belt on the outside. In addition, the belt load changes according to the area where the belt turns around the pulley, resulting in asymmetrical displacement as shown in Fig. 11.

Furthermore, pulley width is widened in the area where the belt turns, and narrowed in the area where the belt does not turn around the pulley.

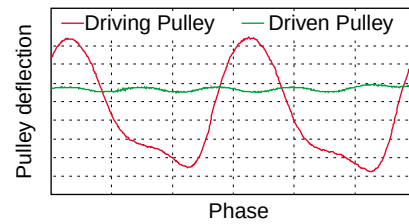


Fig. 11 Pulley deflection

As a result, the load acting on the V-surface of the element increases at the pulley entrance and exit as shown in Fig. 12.⁽⁷⁾ From the perspective of the metal belt, this indicates difficulty in both entering and leaving the pulley, which is hard on the elements.

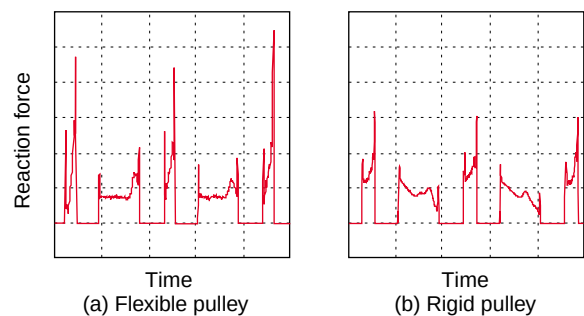


Fig. 12 Reaction force on V-surface

Fig. 13 shows the stress waveform for the innermost layer ring at this time. The influence of pulley deflection on the ring stress can be clearly seen in the turning area of the driving pulley. The stress amplitude also becomes slightly larger as the pulley rigidity decreases.

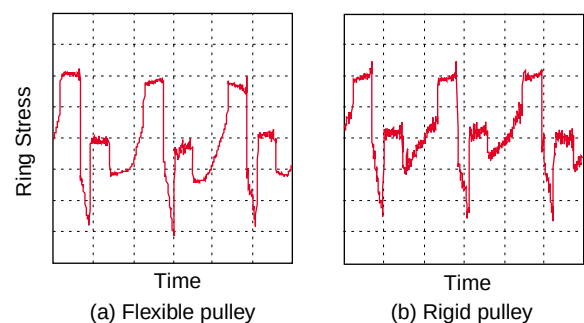


Fig. 13 Influence of pulley flexibility

This is thought to be because the pulley deflection changes the ratio slightly from the top ratio to the OD ratio side, causing the ring bending stress to increase.

5.2 Pulley rigidity balance

As seen from the CVT section, the metal belt is clasped from the right and left by a pair of pulleys having different rigidities.

Normally the amount of pulley deflection on the pulley shaft side is less than that on the movable pulley side, resulting in belt misalignment changes from the dotted line to the solid line as shown in Fig. 14.

Misalignment increases the tip stress across the width of the ring. In order to improve belt durability the design should ensure that the right and left pulley deflections are balanced.

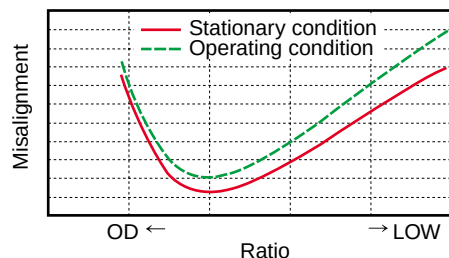


Fig. 14 Influence caused by belt misalignment

6. Metal Belt Analysis System

A dimension input type analysis system, such as that shown in Fig. 15, is an effective means for enabling widespread use by designers of the simulation method developed thus far. This system focuses on the fact that the metal belt element shape topology does not change significantly, and it alters the basic element shape according to the values input by the designer. Therefore, the boundary conditions and contact surface definitions needed for analysis can be automatically set within the system, allowing a metal belt analysis model to be constructed in a short period of time.

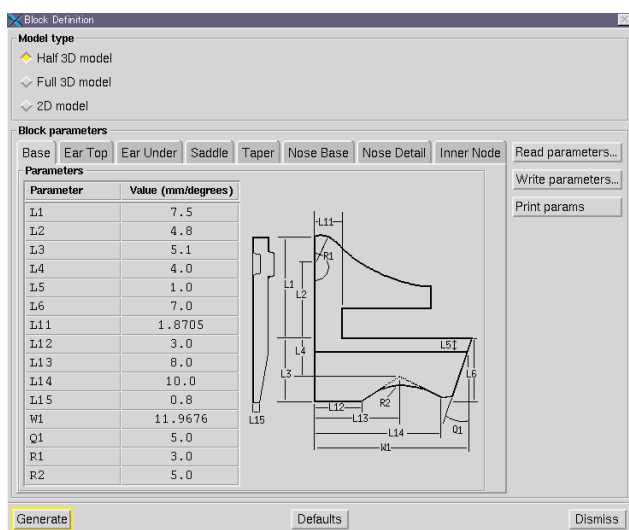


Fig. 15 CVT belt system

7. Conclusion

Simulation technology that determines the stress of the innermost ring at high rotational speeds was developed in order to predict metal belt durability. As a result, the following information was obtained.

- (1) Belt misalignment generates a stress distribution that is skewed in the ring width direction, thus increasing the stress at the ring edges.
- (2) Using the stress amplitude on the inside of the innermost ring as the vertical axis of a SN diagram during high-speed durability tests revealed a correlation with durable life.
- (3) The V-surface load acting on the elements due to pulley rigidity-induced deflection was found to increase markedly at the pulley entrance and exit. Furthermore, increased misalignment due to the left and right pulley rigidity balance must be taken into account in order to enhance belt durability.
- (4) A dimension input type analysis system was established to allow the implementation of the developed simulation technology by designers. This system makes it possible to construct metal belt models in a short time.

8. Acknowledgment

As the need for expanded CVT transmission capacity continues to increase in the future, this technology for judging metal belt durability occupies an important position in determining the basic CVT framework. In the future, the authors intend to further refine accuracy by identifying coefficients of friction, and press forward with the construction of simulation technologies from a designer's viewpoint.

In closing, the authors would like to express their deepest appreciation to related parties at Hibbitt, Karlsson & Sorensen, Inc. for their enormous cooperation over many years in developing solvers and reducing calculation times.

9. References

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