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Research Report

Measurement of the Behavior of a Metal V-belt for CVTs

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ABSTRACT Metal V-belt type continuously variable transmissions (CVTs) offer superior fuel economy and better dynamic performance. As customer demand for higher-specification vehicles has continued to rise, it has become increasingly important to improve the performance of such CVTs, including their power transmission efficiency and torque capacity. To achieve this, it is necessary to carry out a detailed analysis of the behavior of the belt itself, since this is the component that actually transmits the power.

In the present study, we have developed a device that can simultaneously measure the absolute pitch and yaw angles of the belt elements under actual working conditions, without the need to modify the belt. The device was used to clarify the behavior of a metal V-belt of a CVT through one rotation. It was found that both the pitch and yaw angles of the elements increase with decreasing speed ratio in the primary pulley.

Since the yaw angle of the elements has a significant influence on the contact pressure on the pulley surface, it is necessary to reduce the yaw angle in the primary pulley, especially for the lowest speed ratio, in order to increase the torque capacity of the CVT.

KEYWORDS Continuously Variable Transmission, Pulley/Metal V-belt, Measurement, Pitch, Yaw

1. Introduction

Heightened environmental awareness among auto manufacturers and consumers has led to metal V-belt type continuously variable transmissions (CVT) being used in many modern automobile designs. These transmissions offer superior fuel economy and better dynamic performance. As customer demand for higher-specification vehicles has continued to rise, it has become increasingly important to improve the performance of such CVTs, including their power transmission efficiency and torque capacity, etc. To achieve this, it is necessary to carry out a detailed analysis of the behavior of the belt itself, since this is the component that actually transmits the power.

The literature contains several examples of belt behavior measurement methods that can recognize minute movements of the belt.[1,2] To the best of our knowledge, however, there have been no detailed studies of the belt behavior under actual working conditions.

In the present study, we have developed a device that can simultaneously measure the absolute pitch and yaw angles of the belt elements under actual working conditions, without the need to modify the belt. The device was used to clarify the behavior of a metal V-belt of a CVT through one rotation.

Furthermore, we considered the relationship between the increase in the contact pressure on the pulley surface, whereby the wear of the pulley surface increases, and the behavior of the belt.

2. Method of Measuring Belt Behavior

2. 1 Measuring the Element Inclination Angle

The metal V-belt of a CVT features many metal elements supported by two sets of laminated rings, as shown in **Fig. 1**. Power is transmitted from the primary pulley to the secondary pulley by both pulleys clamping this belt from both sides. Therefore, before we can improve the power transmission efficiency and the torque capacity of a metal V-belt type CVT, we have to be able to observe how these elements behave in the pulleys.

In order to observe the movement of an element, its passage time lag is measured with two or more displacement sensors.

The inclination angle of the element is obtained from the belt speed and the distance between the sensors. Here, the pitch of an element to be measured is defined as its rotation around a rocking edge, while its yaw is defined as the rotation around the symmetrical axis of an element. Therefore, the pitch angle is obtained from the signal phase difference between the sensors that are arranged along the vertical axis of the element. The yaw angle is obtained from the signal phase difference between those sensors that are arranged along the horizontal axis of the element (**Fig. 2**).

2. 2 Device for Observing Element Inclination Angle

It is very difficult to accurately observe the movement of an element, because each is a very small part, approximately 30 mm wide, 15 mm high, and 2 mm thick. Conventionally, therefore, it has been necessary to attach a displacement enlarger to the element so that the displacement sensitivity can be increased (**Fig. 3**). [1]

Unfortunately, the use of a displacement enlarger gives rise to following problems.

(1) The displacement enlarger vibrates as the belt rotates, and this disturbance component is superimposed on the original signal, thus degrading the signal-to-noise (SN) ratio.

(2) Measurement becomes difficult when the input speed is high because the increase in the mass and the vibration caused by the attachment of the displacement enlarger adversely affect the movement of the element.

(3) The overall movement of the belt can not be observed because the object of measurement is limited to that specific element to which the displacement enlarger is attached.

To overcome these problems, we implemented the following improvements, and developed a device for measuring the inclination angle of an element under actual operating conditions, without the need for a displacement enlarger (**Fig. 4**).

(1) We installed eddy current displacement sensors with a sensing surface diameter of approximately 2 mm, at a position approximately 0.3 mm from the element so as to obtain the required sensor sensitivity.

(2) To prevent the element from touching the sensor, and to maintain the required sensor sensitivity despite the radial displacement of the belt, we installed a sensor head position control servomechanism that maintains a constant distance of approximately 0.3 mm

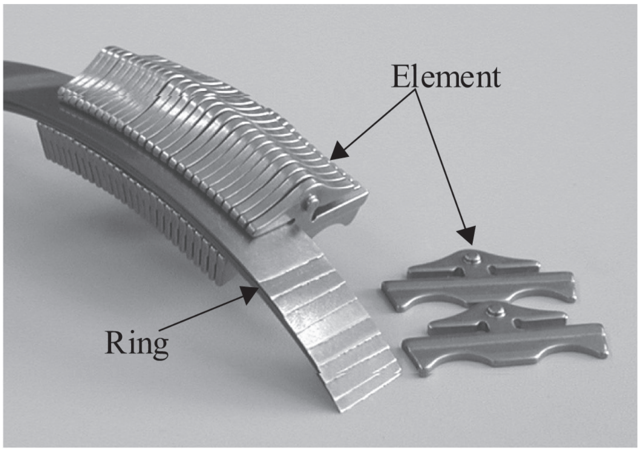

Fig. 1 Structure of a metal V-belt.

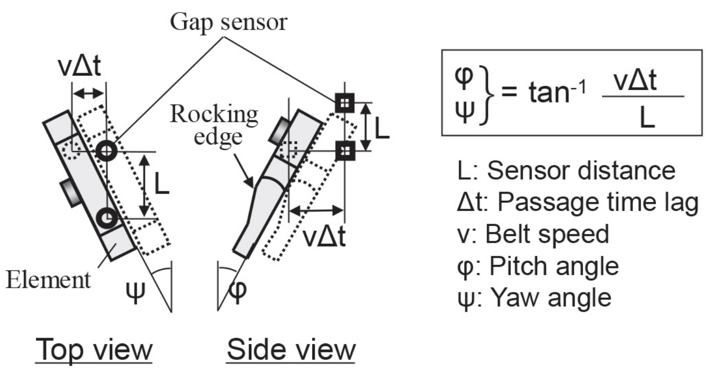

Fig. 2 Measurement principle of element inclination angles.

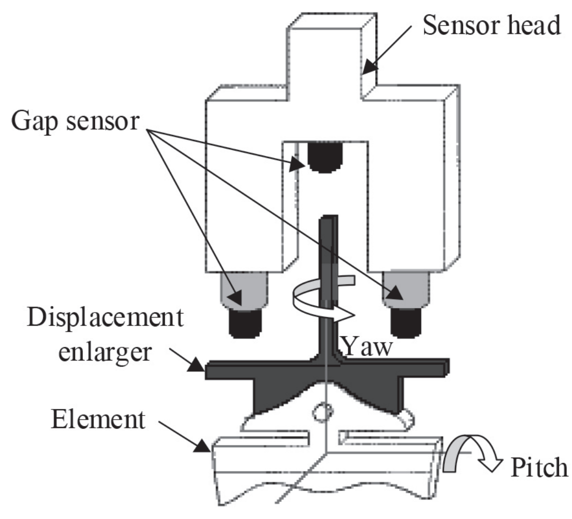

Fig. 3 Example of displacement enlarger.

between the sensor and the element (**Fig. 5**).
(3) To prevent mutual magnetic field interference between the three sensors used to monitor the element, we attached metal interference prevention rings that also served to protect the sensors.

The aforementioned improvements allow this device to measure the absolute pitch and yaw angles of the elements simultaneously under actual working conditions without any modification to the belt.

2. 3 Measurement Conditions and Data Processing

We performed our measurements at a speed ratio γ (secondary pitch diameter / primary pitch diameter) of 2.4, mainly because the belt behavior greatly influences the power transmission efficiency and the torque capacity of metal V-belt CVTs at $\gamma = 2.4$ (the lowest speed ratio). For our measurements, we used an input speed of 1000 rpm, an input torque of 50-200 Nm, and a clamping force safety factor (SF) of 1.5. We used belts from a 2.0-liter class CVT for our measurements. The inclination angle of the element is measured from the vicinity of the inlet to the vicinity of the outlet of the primary and secondary pulleys.

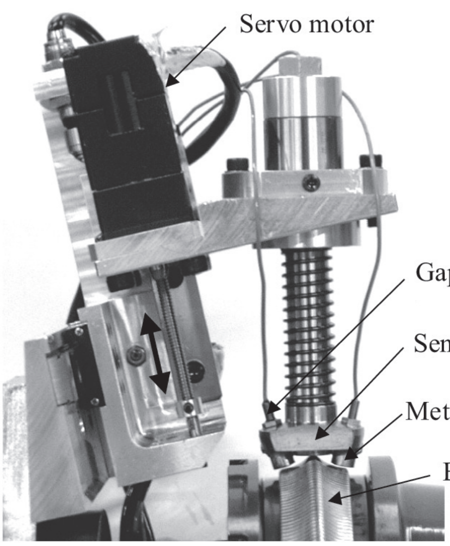

Fig. 4 Element inclination angle measurement device.

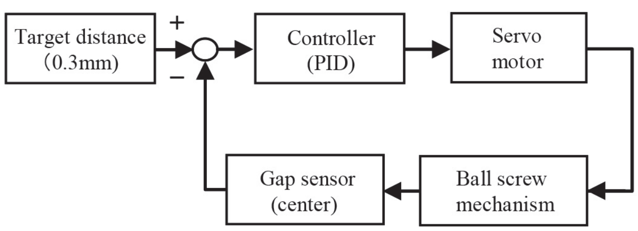

Fig. 5 Sensor head position control system.

To measure the absolute inclination angle of an element correctly, it has been necessary to correct for minute angle errors in the sensor head installation. We corrected these angle errors by using a calibration ring inscribed with the pitch and yaw angles, and then simulating the elements instead of using an actual belt.

The inclination angles of all the elements in the belt can be observed individually using this measurement method. In the experiments described in this report, the inclination angle was obtained by averaging the measured inclination angles for ten rotations, so as to examine the overall movement of the belt.

3. Belt Behavior Measurement Results

3. 1 Element Inclination Angle in Primary Pulley

Figure 6 shows an example of the measured element pitch angle in the primary pulley. The vertical axis indicates the backward tilting pitch angle. When the axis of symmetry of an element corresponds to the radial direction of the pulley, the pitch angle is said to be 0 degrees. The horizontal axis indicates the measuring position in the pulley. The mid point is defined as being 0 degrees and the inlet side is given by a negative value. The pitch in the primary pulley is a backwards tilt and the angle is small from the inlet to the mid point but this roughly doubles after the mid point. Moreover, the pitch angle after the mid point increases with an increase in the input torque.

We believe that, under these measurement conditions, the mid point of the pulley corresponds to the region where the idle arc transitions to the active arc and a backward tilting moment is generated by the difference in the action points of the pulley frictional force and the element compression force in the active arc.

Figure 7 shows an example of the measured element yaw angle in the primary pulley. The vertical axis indicates the counterclockwise yaw angle (as viewed from above). When the rocking edge of the element corresponds to the direction of the rotation axis of the pulley, the yaw angle is defined as being 0 degrees. The yaw angle in the primary pulley is large from the inlet to the mid point but it is roughly reduced by half after the mid point. Moreover, the yaw angle increases with an increase in the input torque over the entire pulley.

Although there are minute gaps between the elements in the idle arc, these gaps disappear as a result of the minute slip of the elements for the pulley in the active arc.(3) Therefore, we believe that the yaw angle is reduced in the active arc because the preceding part of the element is pushed back by the preceding element.

Figure 8 shows the measured element yaw angles at the inlet to the primary pulley for five different belts. The vertical axis in the figure indicates the yaw angles. A clockwise inclination is indicated by the black while a counterclockwise inclination is indicated by the white. The element yaw angle for all the belts becomes almost the same although the direction of the yaw differs for each belt.

As shown in **Fig. 9**, the yaw limit angle, which is defined as the maximum angle to which an element can incline within the clearance between the nose and the hole, was estimated based on 3D CAD. As a result, it was found that the yaw limit angle in the primary pulley is roughly equal to the measured yaw angle at $\gamma = 2.4$, as shown in Fig. 8. Therefore, we assume that an element inclines to an extent approaching the limit angle at the inlet of the primary pulley.

3. 2 Element Inclination Angle in Secondary Pulley

Figure 10 shows an example of the measured element pitch angle in the secondary pulley. The pitch angle is an almost constant backwards tilt in the secondary pulley, which increases slightly near the outlet as the input torque is increased.

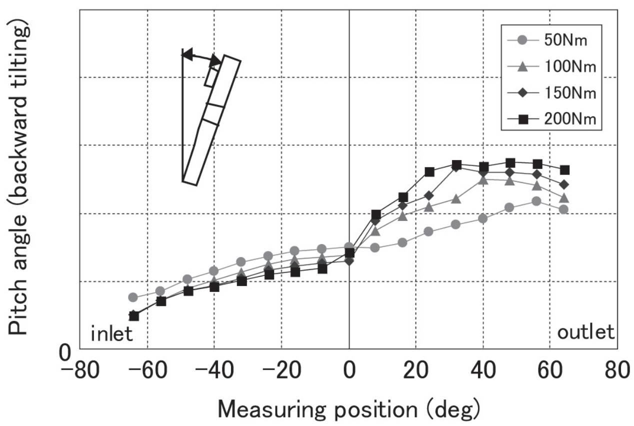

Fig. 6 Measurement results: element pitch angle in primary pulley ($\gamma = 2.4$).

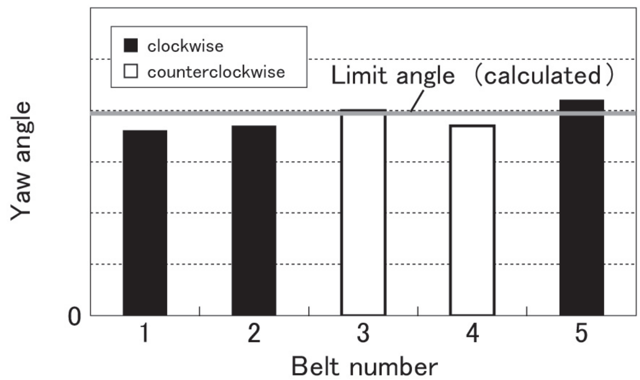

Fig. 8 Measurement results: element yaw angle at inlet to primary pulley ($\gamma = 2.4$).

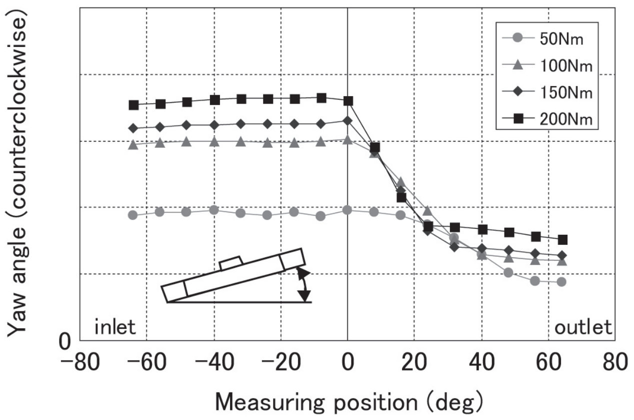

Fig. 7 Measurement results: element yaw angle in primary pulley ($\gamma = 2.4$).

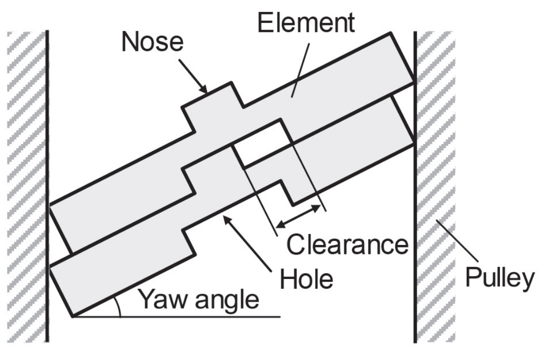

Fig. 9 Cross sectional sketch of element nose and hole.

It is thought that the element inclination change in the secondary pulley is smaller than that in the primary pulley because the elements don't move easily due to their being compressed against each other, such that there is no gap between the elements in the secondary pulley.

Figure 11 shows an example of the measured element yaw angle in the secondary pulley. The yaw angle in the secondary pulley is much smaller than that in the primary pulley. Moreover, the yaw angle remains almost constant from the inlet to the outlet of the secondary pulley and it increases with the input torque.

We believe that this is caused by the elements being compressed against each other from the straight segment of the belt before the secondary pulley and the reduction in the yaw angle caused by minute slip of the elements is suppressed in an active arc unlike the primary pulley.

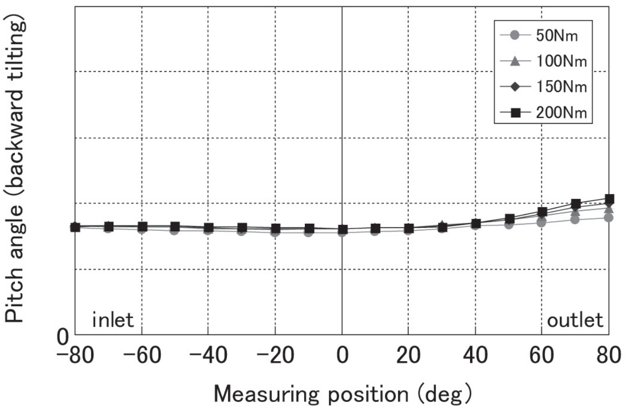

Fig. 10 Measurement results: element pitch angle in secondary pulley (γ = 2.4).

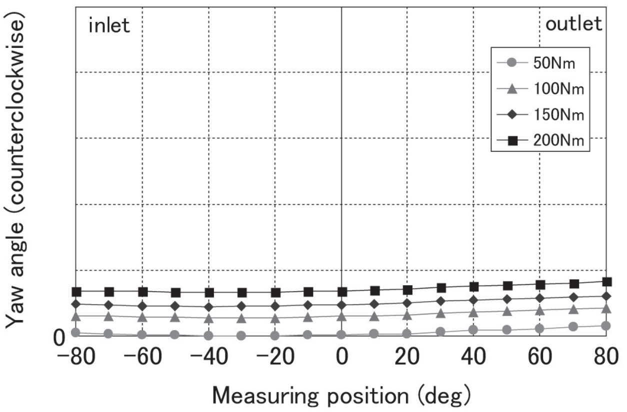

Fig. 11 Measurement results: element yaw angle in secondary pulley (γ = 2.4).

4. Consideration of Belt Behavior

To better understand the behavior of the belt, we went on to measure the inclination angles of the elements under other conditions.

Figures 12 and **13** show examples of the measured element pitch and yaw angles in the primary pulley when γ is changed. To make these measurements, we set the input torque to a constant 200 Nm because the inclination angle varies greatly under this condition. The element pitch and yaw angles change very little when the speed ratios are for high or a constant speed ($\gamma \leqq 1$). On the other hand, the element pitch and yaw angles change considerably when the speed ratios are for low ($\gamma > 1$). It can be seen that the pitch and yaw angles change greatly, especially at $\gamma = 2.4$ (the lowest speed ratio).

It is thought that any large change in the inclination angles of the elements will be detrimental to the power transmission efficiency and torque capacity of a metal V-belt CVT. Therefore, to further improve the performance of a CVT, it will be necessary to minimize the inclination angles of the elements in the primary pulley for low speed ratios.

Figures 14 and **15** show examples of the measured element pitch and yaw angles in the primary pulley when SF is changed. For this measurement, the speed ratio was fixed to 2.4 and the input torque was a constant 100 Nm. The pitch and yaw angles at the inlet

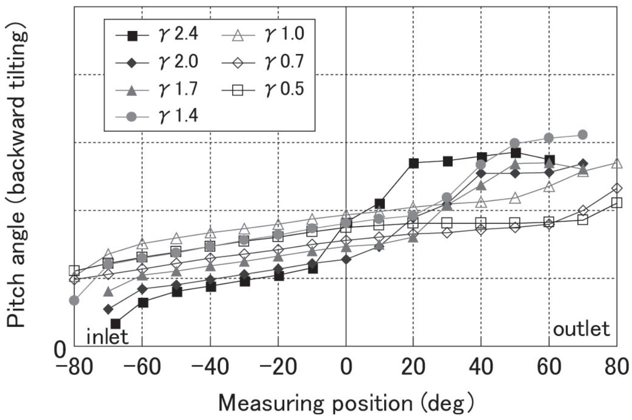

Fig. 12 Measurement results: element pitch angle in primary pulley for different γ (200 Nm).

of the pulley are constant and independent of the value of SF. On the other hand, the sudden change position of the pitch and yaw angles in the pulley moves towards the outlet as SF increases.

From the above, we can understand that the element inclination can change considerably, even though the clamping force is large.

Moreover, the position at which the element pitch and yaw angles change suddenly in the primary pulley moves towards the outlet with an increase in the clamping force. It has been proven that the sudden change position of the element pitch and yaw angles in the primary pulley is the transition region from the idle arc to the active arc, as described in Section 3. 1.

Therefore, we can assume that this measuring method can be used to determine a boundary between the idle and active arcs in the primary pulley without any modification to the belt under actual working conditions, while preventing the macro slip that occurs with an increase in the active arcs.

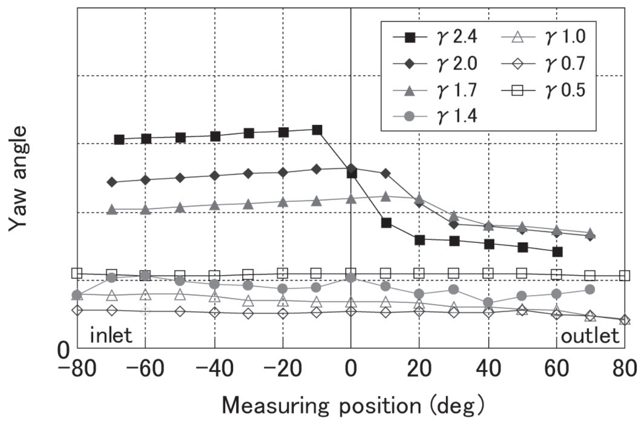

Fig. 13 Measurement results: element yaw angle in primary pulley for different γ (200 Nm).

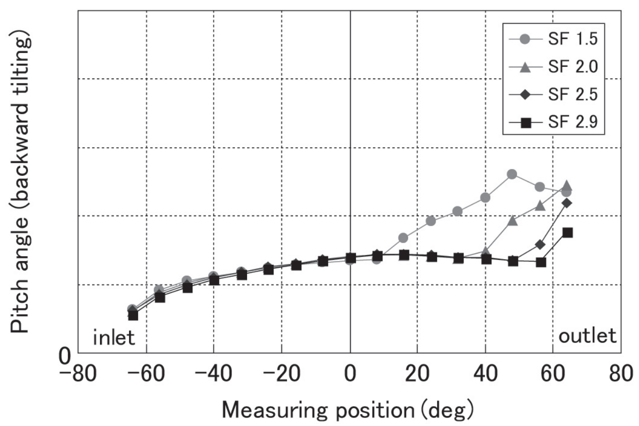

Fig. 14 Measurement results: element pitch angle in primary pulley for different SF (γ = 2.4, 100 Nm).

5. Relationship between Belt Behavior and Contact Pressure on Pulley Surface

In this section, we examine the relationship between the belt behavior and the contact pressure on the pulley surface, which influences the torque capacity of the CVT.

If the element inclination angle is changed from the default value of 0 degrees (referred to as the standard condition), the position of the clamping force on the pulley will either vary or the force will be concentrated on one spot, possibly leading to an increase in the contact pressure on the pulley surface. To investigate this, the finite element method (FEM) was used to evaluate the dependence of the contact pressure on the element inclination angle. To simplify the FEM calculations, the flank surface that forms the element's area of contact with the pulley was assumed to be a flat plane.

The results of the calculations are shown in **Fig. 16**. The vertical axis indicates the ratio of the contact pressure on the pulley surface to that for the standard condition, while the horizontal axis indicates the element inclination angle normalized by the maximum yaw and pitch angles. It can be seen that the contact pressure increases about three times larger with yaw angle than with pitch angle.

In general, it is necessary to increase the contact

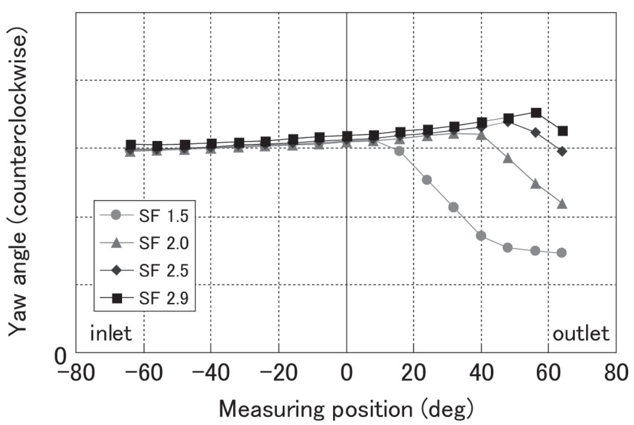

Fig. 15 Measurement results: element yaw angle in primary pulley for different SF (γ = 2.4, 100 Nm).

pressure on the pulley surface in order to increase the torque that the CVT can transmit. However, if the yaw angle increases so much that the maximum allowable contact pressure is exceeded, this would lead to wear of the pulley surface.

To increase the torque capacity of a CVT that uses a metal V-belt, it is therefore necessary to reduce the yaw angle of the element (Fig. 8) in the primary pulley for the lowest speed ratio, at which the yaw angle becomes largest. An effective method for preventing an increase in the yaw angle is believed to involve reducing the in-plane clearance between the element's nose and hole to an appropriate level (Fig. 9).

6. Summary

(1) We have developed a device that can simultaneously measure the absolute pitch and yaw angles of the belt elements under actual working conditions, without the need to modify the belt.
(2) Both the pitch and yaw angles of the elements increase with decreasing speed ratio in the primary pulley.
(3) The element pitch and yaw angles change suddenly near the mid point of the primary pulley.
(4) The sudden change position of the element inclination angle in the primary pulley moves towards the outlet with an increase in the clamping force.
(5) Since the yaw angle of the elements has a significant influence on the contact pressure on the pulley surface, it is necessary to reduce the yaw angle in the primary pulley, especially for the lowest speed ratio, in order to increase the torque capacity of the CVT.

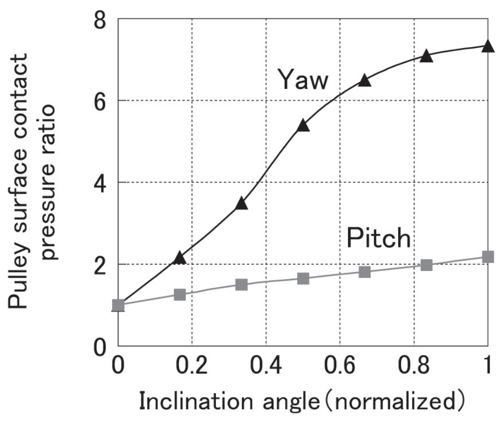

Fig. 16 Calculation results: pulley surface contact pressure ratio for element inclination angle ($\gamma = 2.4$, 200 Nm).

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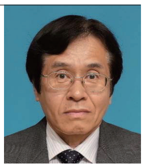

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