

# Analysis of the Accessory Belt Running Off of the Pulley in Automotive Engines

Atsuo FUJII\*

Shougo YONEMOTO\*

Kazuma OKUDA\*

Kiyoshi MIYAZAKI\*

Hiroshi MIYAZAWA\*

Seiji FURUMATA\*

---

## ABSTRACT

Having established the measurement technology to measure accessory belt behavior using laser displacement measurement methods, we were able to clarify the mechanisms causing the belt to run off of the pulley by analyzing the correlation between the belt's behavior and fluctuations in input to the belt and by performing belt behavior simulation. Based on our findings, we were able to create a design tool. We clarified the fact that the belt runs off of the pulley if a resonance occurs due to the accessory belt's natural frequency equaling 1/2 of the frequency of belt length fluctuation in the belt tension direction caused by crankshaft torsional vibration and if the length fluctuation in the belt tension direction exceeds a threshold value. We also found that lateral vibration occurred due to the existence of a lateral movement natural vibrational mode in the belt itself. Based on our findings, we created a belt movement limit map and constructed a belt run off simulation enabling us to propose design tools to prevent the belt from running off of the pulley. In addition, we provided an example of a method used to investigate the prevention of the belt running off the pulley by presenting the effects of design parameters for crankshaft related parts.

---

## 1. Introduction

Increased interest in promoting global environmental protection over the years has led to calls for the development of automotive engines that are more environmentally sound. This movement has been paralleled by a demand for high engine speed, high output, the most basic aspects of engine performance. Therefore, research is needed to resolve the various problems that arise from engine vibration at high engine speeds.

High speed engines tend to increase the circumferential speed of an automotive engine's accessory belt (i.e., V-ribbed belt) and can potentially result in degraded belt performance. In fact, problems such as the belt running off of the pulley have not been uncommon in actual engine development. However, the vibrational mode and mechanism that are behind the causes of a belt running off of the pulley have not been determined and so have resulted in enormous amounts of time and effort to develop countermeasures. V-ribbed belts used as accessory belts create a spring/mass vibration system between the crankshaft pulley and the various accessories (e.g., alternator, air conditioning compressor, and power steering pump) such that torsional vibration occurring in the crankshaft is transmitted from the crankshaft pulley to the accessories via the belt. Various

vibrational modes can be exhibited at this time depending on such factors as the accessories' inertial moment and belt elasticity. Research on belt behavior and rotational fluctuation in accessory components has not been extensive, however, due to the lack of quantifying technologies. Today, however, advanced instrumentation and sophisticated technologies for data processing make it possible to investigate multiple phenomena simultaneously and in real time. Thus, analysis of the behavior of high-rpm pulleys and accessory belts is now possible.

This paper discusses a measurement method for the behavior and quantitative displacement of accessory belts in high speed engines, the mechanism of a belt running off of a pulley, how the related quantitative limits are established, and the process of defining specifications for components related to the accessory belt.

## 2. Analysis of the Mechanism of a Belt Running Off of a Pulley

### 2.1. Overview of the Accessory Belt System

Research on why an accessory belt runs off of a pulley began with fixed-tension, biaxial systems having one accessory (Fig.1) but has expanded to include systems with up to two accessories and three axes. This paper, however,

---

\* Tochigi R & D Center

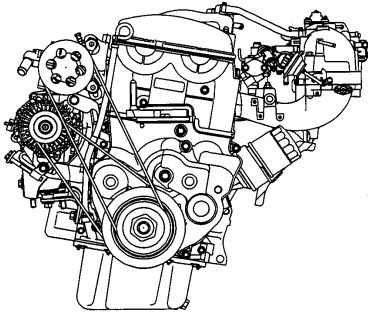


Fig.1 Structure of accessory belt system

deals with biaxial systems. The engine used was the 2.3-liter DOHC VTEC (Valve Timing and lift Electronic Control) engine shown in Fig.1.

## 2.2. Factors that Degrade Belt Behavior

The authors have investigated the factors that degrade belt behavior by comparing the fluctuations in angular velocity and axis direction, etc., that occur in the two pulleys and the belt behavior in the portion not in contact with the pulleys. This research assumes that the belt portion around the crankshaft and accessory pulley functions integrally, with no slippage or lift relative to the pulley.

Figs.2-a and 2-b show the variables used as influential factors in the analysis, along with the symbols for those

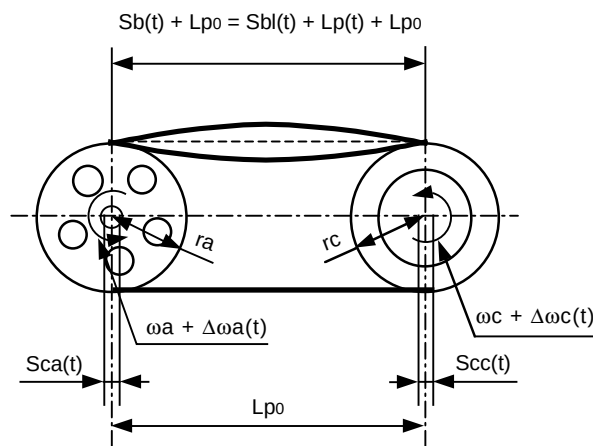


Fig.2(a) Factors in the changing length of the accessory belt between the accessory pulley and the crankshaft pulley

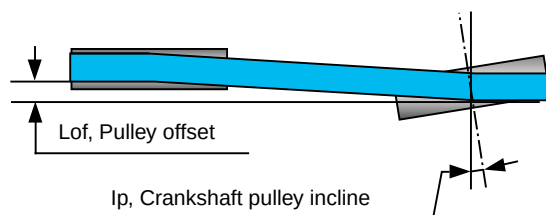


Fig.2(b) Factors in crankshaft axial direction fluctuation

variables. The two factors contributing to the belt running off of the pulley are described below.

- (1) Belt length fluctuation in the belt tension direction ( $S_b(t)$ , mm): Fluctuation in the length of the belt portion not in contact with the pulleys.

This is due to fluctuation in pulley circumferential movement length caused by fluctuation in the angular velocity of the crankshaft and accessory pulley (hereinafter referred to as crankshaft pulley circumference fluctuation and accessory pulley circumference fluctuation, expressed as  $S_{pc}(t)$  and  $S_{pa}(t)$ , respectively), and to fluctuation in the belt length of the portion between but not in contact with the crankshaft pulley and accessory pulley axes due to pulley run-out ( $L_p(t)$ ). Thus,  $S_b(t)$  is expressed with the following equation.

$$S_b(t) = S_{bl}(t) + L_p(t) = S_{pc}(t) + S_{pa}(t) + S_{cc}(t) + S_{ca}(t) \quad (1)$$

As expressed in equations (2) and (3) below, each pulley's circumferential fluctuations  $S_{pc}(t)$  and  $S_{pa}(t)$  can be determined by integrating angular velocity fluctuations ( $\Delta\omega_c(t)$  and  $\Delta\omega_a(t)$ ) and multiplying this by the radius of each pulley ( $r_c$  and  $r_a$ ). The angular velocity fluctuation is found by subtracting the average angular velocity ( $\omega_c(t)$  and  $\omega_a(t)$ ) from the crank pulley and accessory pulley angular velocity.

$$S_{pc}(t) = r_c \int \Delta\omega_c(t) dt \quad (2)$$

$$S_{pa}(t) = r_a \int \Delta\omega_a(t) dt \quad (3)$$

$\Delta\omega_c(t)$ : Crankshaft pulley angular velocity fluctuation  
 $\Delta\omega_a(t)$ : Accessory pulley angular velocity fluctuation  
 $r_c$ : Crankshaft pulley radius  
 $r_a$ : Accessory pulley radius

- (2) Fluctuation in the thrust direction ( $S_{bs}(t)$ , mm):  $S_{bs}(t)$  is defined as fluctuation in the pulley axial thrust direction occurring between the pulleys (i.e., in the portion not in contact with the pulleys) due to axial incline in the crankshaft pulley and accessory pulley, and to pulley offset ( $L_{of}$ , mm), shown in Fig.2-b.

Thus it is assumed that length fluctuation in the belt tension direction ( $S_b(t)$ ) involves the belt running off of a pulley due to flexure caused by an increase in belt length between the pulleys; and, that fluctuation in the thrust direction ( $S_{bs}(t)$ ) involves belt lateral offset caused by belt fluctuation in the lateral direction during operation.

## 2.3. Measurement Methods

### 2.3.1. High-Speed Camera Method

High-speed cameras (NAC model HSV-500) were used to visually capture belt behavior leading up to the belt running off of the pulley. The two cameras were positioned facing the back surface and a side surface of the belt (Fig.3-a), and were used to videotape the belt at a rate of 250 frames per second. Fig.3-b is an example of the images that were taken. The backface of the belt was painted with ladder-like markings in order to facilitate analysis of belt movement.

### 2.3.2. Laser Displacement Measurement

A laser sensor (Keyence LX2-03; Fig.3-a) was used to

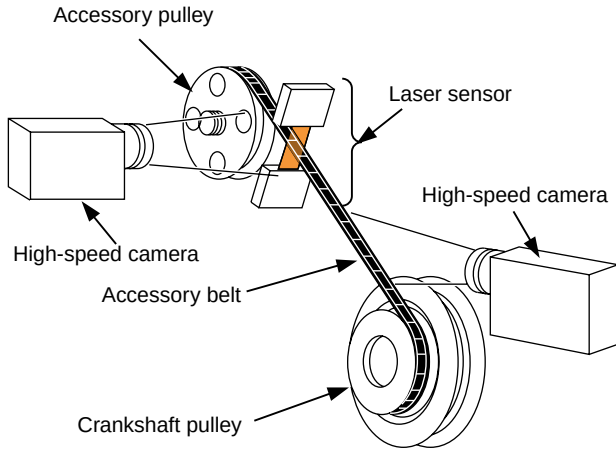


Fig.3(a) Measurement methods of accessory belt movement using a high-speed camera and laser sensor

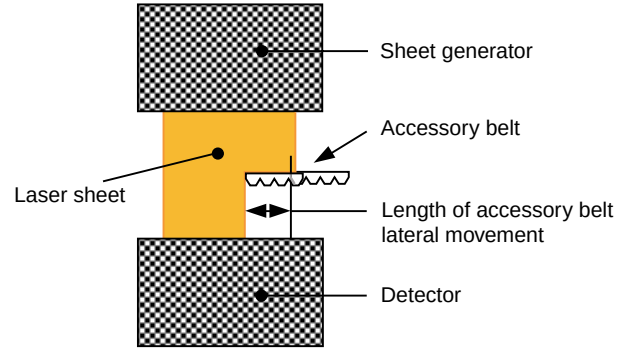


Fig.4 Structure of laser sensor

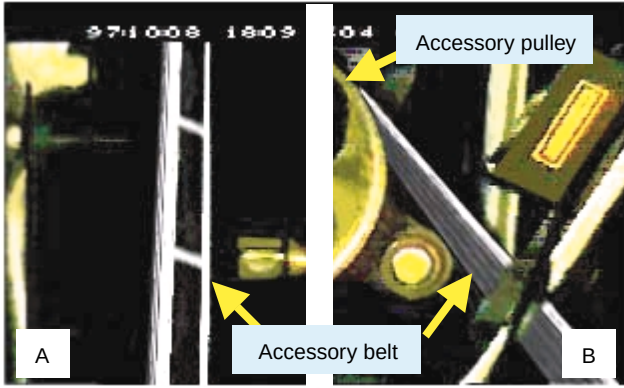


Fig.3(b) Images of the belt's back-surface (A) and side-surface (B) taken with high-speed cameras

precisely quantify belt behavior in the lateral direction after capturing overall belt behavior using the high-speed cameras. This sensor uses a band-shaped laser beam and a linear sensor containing a charged-coupled device (CCD), and provides an output that is proportional to the amount of laser light that is blocked (Fig.4). The setup shown in Fig.4 therefore yields an output that is proportional to belt displacement in the lateral direction. The laser sensor has a response frequency of 256 Hz and a spatial resolution of 0.5 mm, and can measure engine speeds of up to 7700 rpm.

### 2.3.3. Pulley Circumference Fluctuation

Crankshaft pulley circumferential fluctuation ( $S_{pc}(t)$ ) and accessory pulley circumferential fluctuation ( $S_{pa}(t)$ ) were calculated from the angular velocity fluctuation of each pulley axis ( $\Delta\omega_c(t)$  and  $\Delta\omega_a(t)$ ) using equations (2) and (3), and were determined as described below.

First, an accelerometer was mounted to each axis by means of a jig to measure acceleration ( $g_c(t)$ ,  $g_a(t)$ ) at the given mounting radii (crankshaft pulley =  $r_{ac}$ , accessory pulley =  $r_{aa}$ ). These were integrated to determine angular

velocity fluctuation ( $\Delta\omega_c(t)$  and  $\Delta\omega_a(t)$ ). The reason for using two accelerometers was to cancel out components other than angular acceleration fluctuation that can exist when pulleys undergo eccentric motion in opposing sensitive directions.

$$\Delta\omega_c = \frac{1}{r_{ac}} \int g_c(t) dt \quad (4)$$

$$\Delta\omega_a = \frac{1}{r_{aa}} \int g_a(t) dt \quad (5)$$

### 2.3.4. Pulley Fluctuation

Fluctuation due to pulley rotation most likely includes eccentricity of the pulley axis and pulley axis incline relative to the belt line (Fig.2-a). The former was determined by measuring the distance between pulley periphery and two gap sensors positioned at a 90° phase angle relative to each pulley (Fig.5-a).

In the latter, pulley axis mounting and flexion related to belt tension are believed to be factors, as the pulley side surfaces do not move in the same plane. This fluctuation was measured with gap sensors positioned as shown in Fig.5-b.

## 3. Experimentation: Results and Observations

### 3.1 Belt Behavior

Observation of belt behavior using the high-speed cameras and laser sensors revealed four vibrational modes (Fig.6), and showed that the phenomenon of a belt running off of the pulley is caused by lateral movement vibration (Fig.6-d). Fig.7 illustrates positional fluctuation in lateral movement at belt cross-section C-C indicated in Fig.6-d. This positional fluctuation is belt movement in the thrust direction, and also indicates movement of the belt back surface to the outside due to torsion. The images in Fig.3-b clearly show this torsional state: in the left-hand image, belt torsion has caused the markings to slant, whereas in the right-hand image belt torsion is causing the cross-sectional width to change in the manner illustrated in Fig.7. Belt movement in the thrust direction is as great as 30 mm, which is equivalent to two times the pulley width.

To identify the causing behind belt lateral movement vibration, the authors used gap sensors to measure pulley offset, pulley eccentricity, and pulley side surface incline,

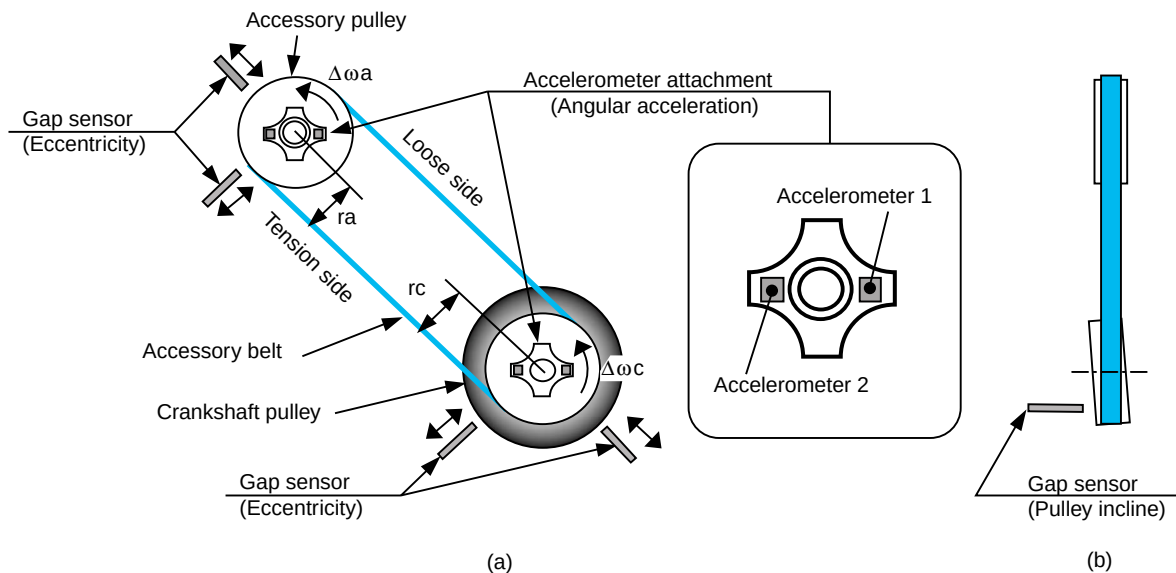


Fig.5 Measurement methods of fluctuation input to accessory belt

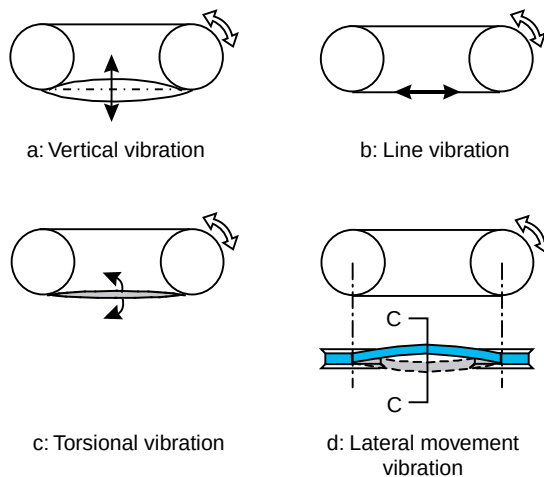


Fig.6 Vibration patterns

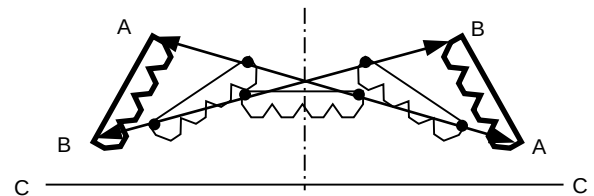


Fig.7 Lateral movement vibration at cross section C-C in Fig.6. Arrows show movement of both sides of the belt

Table 1 Effect level of fluctuation input to belt on belt behavior

| Direction of fluctuation  | Items                                               | Influence  |
|---------------------------|-----------------------------------------------------|------------|
| Crankshaft axis direction | Offset of pulley alignment                          | Negligible |
|                           | Pulley incline                                      | Negligible |
| Belt tension direction    | Pulley eccentricity                                 | Negligible |
|                           | Fluctuation on pulley circumference (by revolution) | Strong     |

but the resultant measurements were not significantly large. This was true with measurements taken up to the maximum allowable values for mass production control. Thus, no causal relationship was detected. The results, shown in Table 1, suggest that belt lateral movement vibration is largely influenced by belt length fluctuation in the belt tension direction, which was therefore made the focus of analysis in subsequent experimentation.

### 3.2. Belt Length Fluctuation in the Belt Tension Direction and Lateral Movement Fluctuation

Pulley circumference fluctuation ( $S_{pc}(t)$ ,  $S_{pa}(t)$ ) and pulley axis run-out ( $S_{cc}(t)$ ,  $S_{ca}(t)$ ) are possible factors in belt length fluctuation in the belt tension direction ( $S_b(t)$ ). As pulley axis run-out has been verified in ordinary engines as being only one-tenth of pulley circumference fluctuation, it was decided that focus would be placed only on pulley circumference fluctuation. Fig.8 gives the waveform of crankshaft pulley circumferential fluctuation ( $S_{pc}(t)$ ) and accessory pulley circumferential fluctuation ( $S_{pa}(t)$ )

calculated with the accelerometer output shown in Fig.5-a for engine speeds of 2000 rpm and 7500 rpm, which are the experimental conditions used to represent stable movement and lateral movement vibration, respectively, in an accessory belt. In the former case, the circumferential fluctuation waveform of both the crankshaft pulley and accessory pulley exhibit the same phase, whereas in the latter case, there is a phase difference of approximately  $80^\circ$  relative to the crankshaft angle (hereinafter " $80^\circ CA$ "). Pulley circumferential fluctuation, which is a second order component relative to the crankshaft angle, is such that the

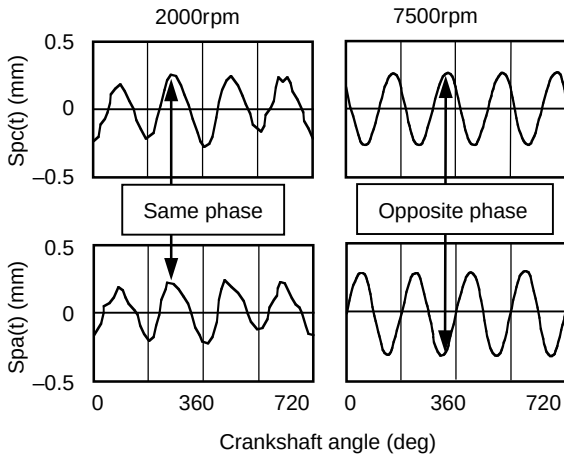


Fig.8 Wave fluctuation on pulley circumference

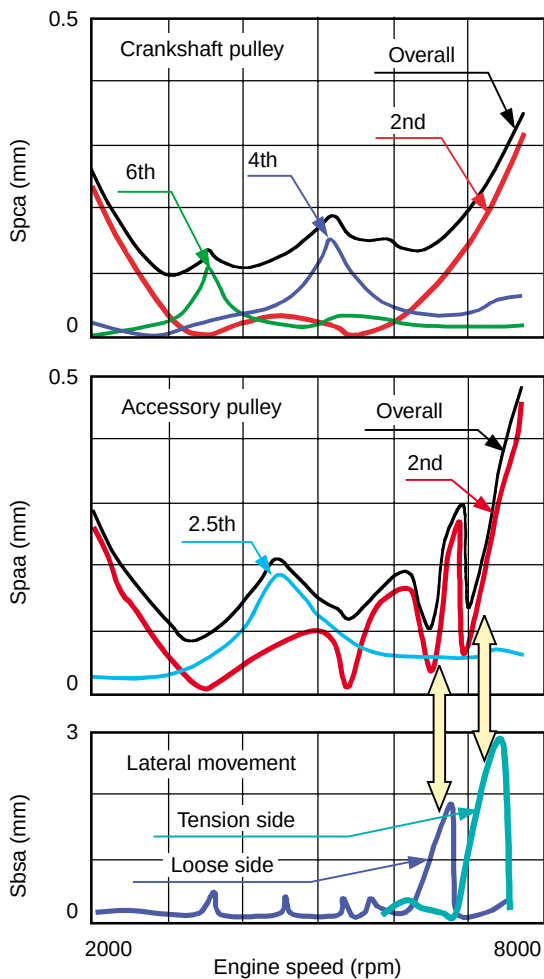


Fig.9 Characteristics of Spca, Spaa and Sbsa vs. engine speed

80°CA phase difference between the two pulleys results in approximately opposite phases. Fig.9 shows the results of using fast Fourier transform analysis (FFT) to track the crankshaft pulley and accessory pulley circumferential fluctuation ( $Spc(t)$  and  $Spa(t)$ ) for the given engine speeds; the trough-to-peak amplitude of belt lateral movement is also shown for comparison. The vertical axis shows, from the

top down, the amplitude of crankshaft pulley circumferential fluctuation ( $Spca$ , mm), amplitude of accessory pulley circumferential fluctuation ( $Spaa$ , mm), and amplitude of accessory belt lateral movement ( $Sbsa$ , mm). Note that the amplitude of both the crankshaft pulley and the accessory pulley circumferential fluctuations have a second order component that rises in the high-rpm zone, and that the amplitude of belt lateral movement also tends to rise along with it. The second order component of  $Spaa$  in Fig.9 suddenly begins to converge at an engine speed of 6300 rpm, then rises sharply at 6500 rpm. This corresponds with the changes in loose-side lateral movement amplitude ( $Sbsa$ ), indicated by arrows in Fig.9. Similarly, the sudden convergence and sharp increase in the second order component of  $Spaa$  beginning at 6800 rpm corresponds with the fluctuation in  $Sbsa$  on the tension side.

Next, Fig.10 shows the second order components of the amplitude of length fluctuation in the belt tension direction, which is a composite value that accounts for the phases of  $Spcc(t)$  and  $Spca(t)$ , as well as the amplitude of belt lateral movement. As engine speed rises from 2000 to 7700 rpm, the waveforms of the crankshaft pulley and the accessory pulley circumferential fluctuations go from having the same phase to opposite phases (Fig.8). Consequently, the amplitude of length fluctuation in the tension direction is added on rather than being cancelled out, showing an increasing value that results in a marked lateral movement amplitude in the area where belt length fluctuation in the

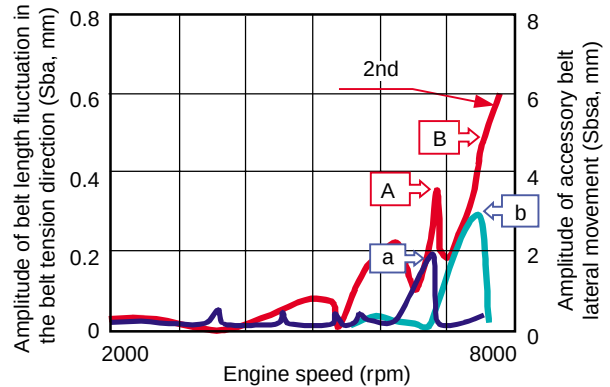


Fig.10 Characteristics of Sba and Sbsa vs. engine speed

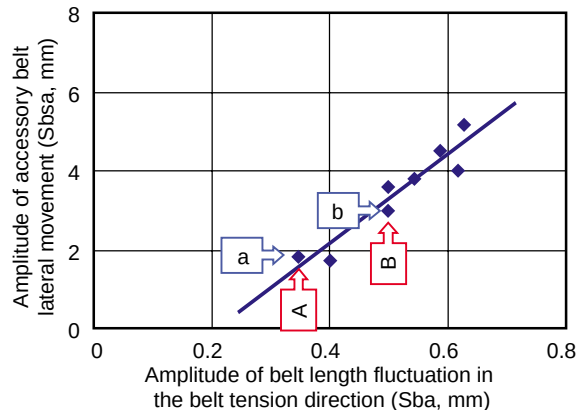


Fig.11 Relationship between Sba and Sbsa

belt tension direction (Sba) exceeds 0.2 mm. Fig.11, in which the amplitude of belt lateral movement from Fig.10 is the vertical axis and the amplitude of belt length fluctuation in the belt tension direction is the horizontal axis, adds the tension-side and loose-side points from Fig.10 (A, B, a, b) and measurements of maximum value for different initial belt tension settings. This graph indicates good correlation between the belt's loose and tension sides, as evinced by the linear distribution of both. Fig.12 shows engine speed and the lateral movement vibration frequency (Hz) at which the accessory belt exhibited lateral movement at different initial tension settings. The one-to-one correlation between the two frequencies suggests that the belt vibration frequency is the belt's natural frequency for each initial tension. The reason that engine speed at peak lateral movement vibration is lower on the loose side in Figs.9 and 10 is that because belt tension is lower on the loose side than on the tension side due to the accessory's rotational resistance, the belt's natural vibrational frequency is also lower on the loose side. Combining the results from Figs.10 and 11 shows that belt lateral movement vibration occurs when engine speed and the belt's natural vibrational frequency corresponds in an engine speed area in which the amplitude of belt length fluctuation in the belt tension direction is 0.2 mm or greater.

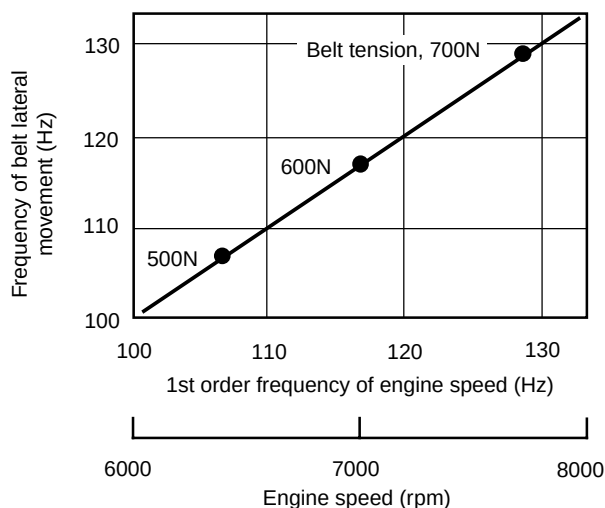


Fig.12 Relationship between engine speed and frequency of belt lateral movement when varying to belt tension

### 3.3. Analyzing the Mechanism of Belt Lateral Movement

#### 3.3.1. Lateral Movement Vibrational Modes

The preceding has shown that when engine speed is high enough to create large belt length fluctuation in the belt tension direction and also matches the belt's natural vibration frequency, the belt resonates and undergoes vibrational movement in the lateral direction. In this section, the mechanism of this lateral movement is considered. Assuming one factor behind this lateral movement is the fact that the belt itself has a natural vibrational mode at which lateral movement occurs, the authors used a finite element model

to perform nonlinear natural vibrational mode analysis.

The one-dimensional string model generally used for approximation in belt vibration analysis, although capable of predicting string vibrational mode, could not predict the vibrational mode of the type of lateral movement seen in actual engines. This is believed to be because this technique cannot account for the asymmetry of mass and stiffness in a belt cross section, which is determined by the core position and rib height. For this reason, the authors performed analysis with a finite element method based on a three-dimensional belt model having the belt shape shown in Fig.13. This model was comprised of a high-stiffness core portion which primarily bears the tensile load, and a rubber portion, with a 100:1 ratio between the stiffness of the former and that of the latter, and an overall belt spring constant of 530 N/mm. The belt length and width used in the calculations were the same as those of the actual belt (352 mm and 14 mm, respectively). The calculations sought to determine the natural vibrational mode with one end of the belt anchored and the other end subjected to a tensile load in the belt tension direction.

Fig.14 shows the results of this analysis. Figs.14-a and 14-b, which view the belt obliquely from above and slightly from above in the belt's longitudinal direction, respectively, show lateral slip to the right and left. The lateral movement from the center line in Fig.14-b and the upward movement of one end in Fig.14-a conform to the lateral movement

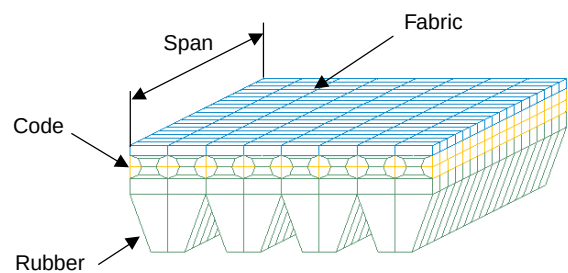


Fig.13 Belt model for FEM

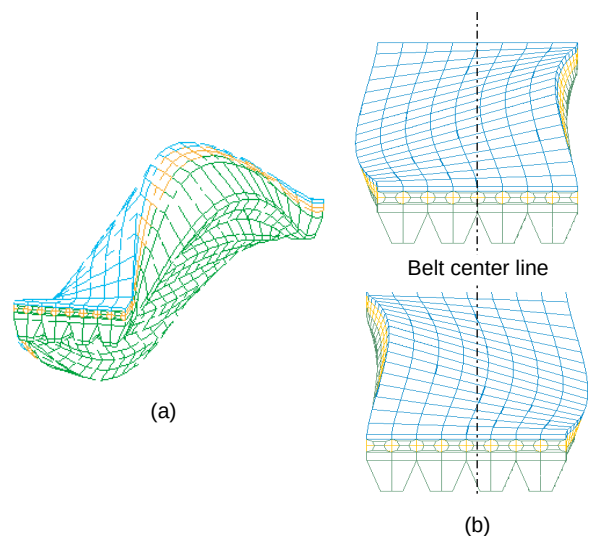


Fig.14 Vibrational mode analysis results of the accessory belts lateral movement

observed in an actual belt. This corroborates the aforementioned findings that lateral movement is a result of the accessory belt's natural vibrational mode in the direction of lateral movement.

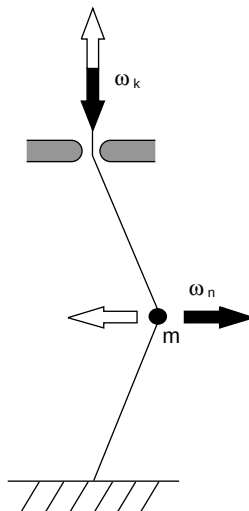
### 3.3.2. Lateral Movement Resonance

Belt vibration, which is a manifestation of changes in tensile load due to fluctuation in pulley angular velocity at the ends of the belt, can be approximated as vibration of a string having mass, as it can be thought of as vibration in a variable elastic system. The vibrational model is shown in Fig.15. The Mathieu equation can be used to judge whether a variable elastic system is stable or unstable (i.e., undergoing resonance). As a precise solution is difficult to arrive at, the authors focused instead on whether the system is stable or unstable at a given time. If stable, then the system is undergoing periodic motion when a disturbance is present. If unstable, then its amplitude increases with time, eventually resulting in resonance. Using the stability criteria of the Mathieu equation, and given a frequency of belt tension fluctuation of  $\omega_k$  and a belt vibration frequency of  $\omega_n$ , as in Fig.15, then motion becomes unstable when<sup>(1)</sup>

$$\omega_n = 1/2\omega_k, \omega_k, 3/2\omega_k, \dots$$

If  $\omega_n$  is substituted with the natural frequency of belt lateral movement ( $\omega_s$ ) and  $\omega_k$  with the frequency of belt length fluctuation in the belt tension direction ( $\omega_b$ ), then the first solution ( $\omega_n = 1/2 \omega_k$ ) suggests that resonance occurs when the natural frequency of belt lateral movement  $\omega_s$  equals one-half of the frequency of belt length fluctuation in the belt tension direction ( $\omega_b$ ). As the frequency of belt length fluctuation in the belt tension direction ( $\omega_b$ ) is equal to twice the engine speed as in Fig.8, this means that  $1/2 \omega_b$  is equal to the engine speed, thus agreeing with the observed results in Fig.12.

When applied to lateral movement vibration in an actual engine, this means, in regards to resonance, that belt tension decreases as mass point  $m$  moves away from the center but



$\omega_k$ ; Frequency of belt tension fluctuation  
 $\omega_n$ ; Frequency of belt vibration

Fig.15 Vibration model of an accessory belt

increases as mass point moves toward the center, with an amplitude that is larger than in the latter states and which most likely increases with time. Moreover, this state of resonance is believed to actually occur as the lateral movement vibration mode in Fig.14, and to be what causes the belt to run off of the pulley.

### 3.4. Criteria for Belt Running Off of the Pulley

In the analysis described in the preceding section (3.3), belt lateral movement was analyzed with the specifications listed as "Sample 1" in Table 2. Next, the authors sought to develop criteria for the belt running off of the pulley based on belt specifications by conducting an experiment with different combinations of belt ribs and belt string length (Table 2). Fig.16 shows, for each number of ribs, the belt length fluctuation in the belt tension direction that caused a belt of the given length to run off of the pulley. This shows that a greater belt length or smaller number of ribs causes the belt to run off of the pulley even with a low belt length fluctuation in the belt tension direction. Thus, when belt length and belt length fluctuation in the belt tension direction are below the line for a given number of ribs, then the belt will not run off of the pulley, and the design can be judged appropriate.

Although belt length fluctuation in the belt tension direction and belt lateral movement are both possible variables for criteria for belt running off of the pulley, the

Table 2 Variations of the tested belt

|          | Number of rib |   |   | Belt string length (mm) |     |     |
|----------|---------------|---|---|-------------------------|-----|-----|
|          | 4             | 5 | 6 | 282                     | 317 | 352 |
| Sample 1 | ○             |   |   |                         |     | ○   |
| Sample 2 |               | ○ |   |                         |     | ○   |
| Sample 3 |               |   | ○ | ○                       |     |     |
| Sample 4 |               | ○ |   | ○                       |     |     |
| Sample 5 |               |   | ○ |                         | ○   |     |
| Sample 6 |               | ○ |   |                         | ○   |     |

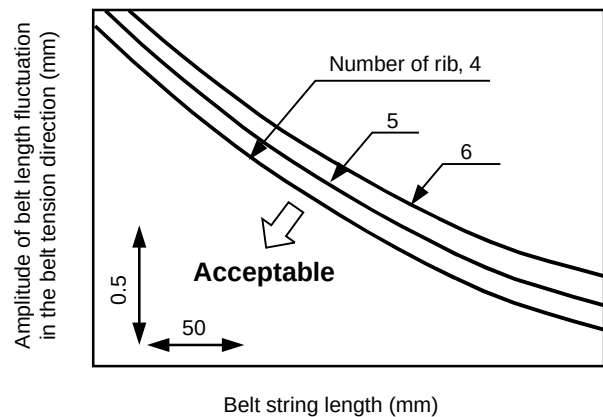


Fig.16 Judgement graph for the accessory belt running off of the pulley

authors selected the former because of its good reproducibility and used it in simulation of a belt running off of the pulley, described in the following section.

#### 4. Design Tools

This section uses the analysis results described in the previous section to describe “simulation of the accessory belt running off of the pulley”. This is a design tool that can be used to predict and prevent an accessory belt running off of the pulley when designing components related to the belt. This process is described using an example application.

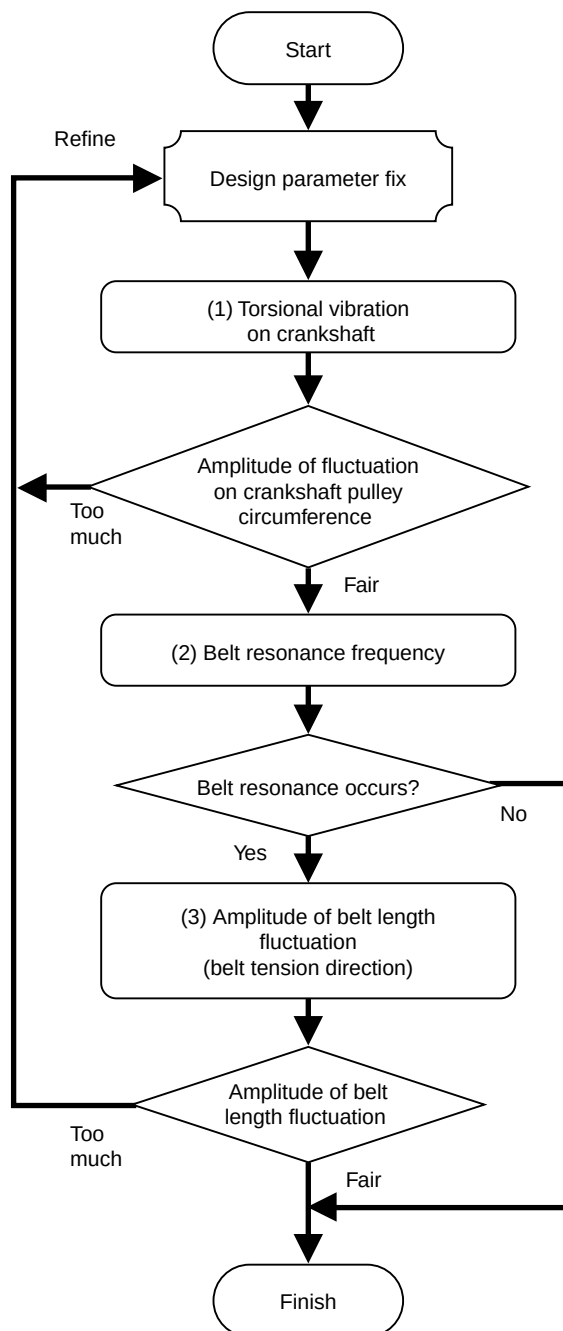


Fig.17 Design flow

#### 4.1. Overview of Simulation

As the flowchart in Fig.17 illustrates, the simulation of an accessory belt running off of the pulley comprises these primary parts: (1) crankshaft torsional vibration simulation, (2) belt natural frequency simulation, and (3) simulation of belt length fluctuation in the belt tension direction, the input/output unit, and the judgment unit.

##### (1) Crankshaft torsional vibration simulation

Crankshaft torsion analysis entails calculating (with the Holzer equation) the angle of torsion from crankshaft dimensions and combustion pressure.

##### (2) Belt natural frequency simulation

Belt vibration analysis entails calculating the belt's natural frequency from belt specifications and accessory layout to determine whether the belt natural frequency falls within the engine's operating speed. If it does not, then belt vibration will not occur, and so design review is concluded at this point.

##### (3) Simulation of belt length fluctuation in the belt tension direction

Analysis of belt length fluctuation in the belt tension direction entails using the analysis model in Fig.18 to perform transient response analysis to calculate a fluctuation response that accounts for inertial mass on the accessory pulley side by defining excitation frequency as the crankshaft-side fluctuation obtained with crankshaft torsional vibration simulation. This yields the time series fluctuation shown in Fig.19. Taking phase difference in this fluctuation into account results in the

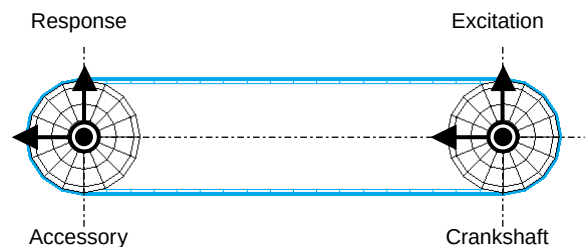


Fig.18 FEM model

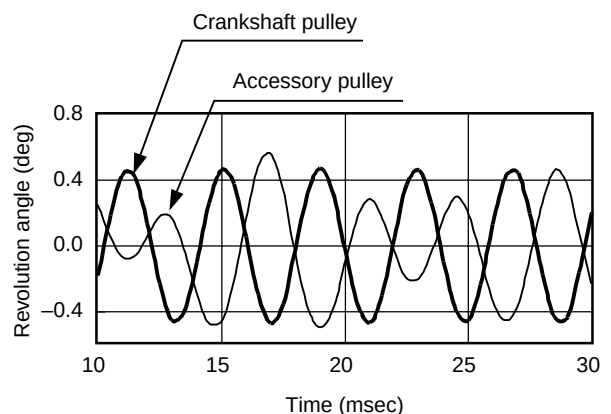


Fig.19 Simulation results of the crankshaft and accessory pulley angle of fluctuation during rotation

belt length fluctuation in the belt tension direction shown in Fig.20. This value is then evaluated with the aforementioned judgment map for belt length fluctuation in the belt tension direction (Fig.16).

#### 4.2. A Review of an Example Using the Method for Preventing Belt Running Off of the Pulley

Fig.21 lists the parameters for assessing effectiveness in preventing a belt from running off of the pulley. Fig.22 shows those parameters in which improvement was clear. Accessory pulley hub inertial mass, crankshaft pulley damper frequency characteristics, and crankshaft pulley inertial mass were examined beyond the range of mass-production engines, but there was no significant improvement: belt lateral movement was roughly 90% that of the base engine in all cases. In contrast, substantial improvements were achieved for metal clearance (only 76% of the base engine at minimum tolerance), which affects crankshaft torsion at angle, and for journal diameter, which affects crankshaft rigidity: belt lateral movement was halved by increasing the diameter from 50 mm to 55 mm. In the latter case, the absolute value of belt lateral movement was reduced

substantially, from 4.2 to 2.4 mm, while a journal diameter of 55 mm resulted in no cases of the belt running off of the pulley despite its frequent occurrence with a 50 mm diameter journal in the experimentation (Fig.23).

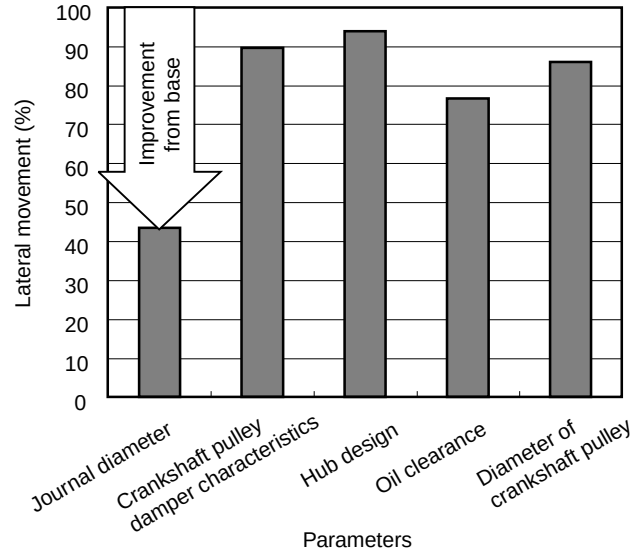


Fig.22 Effects of design parameters on accessory belt lateral movement

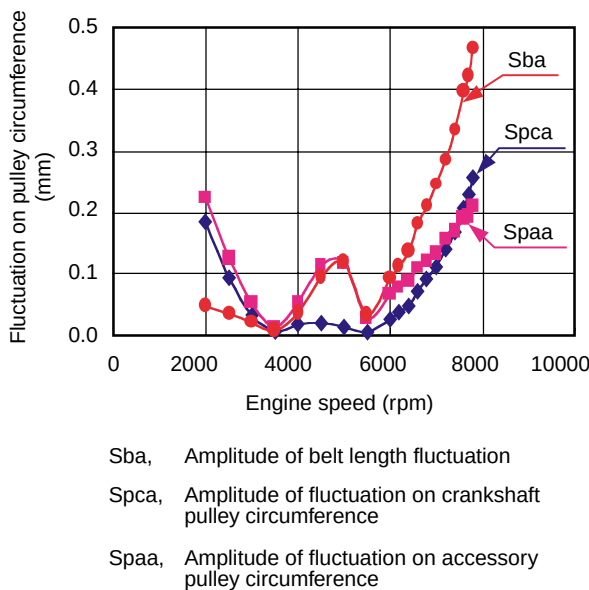


Fig.20 Simulation results of amplitude of fluctuation on pulley circumference

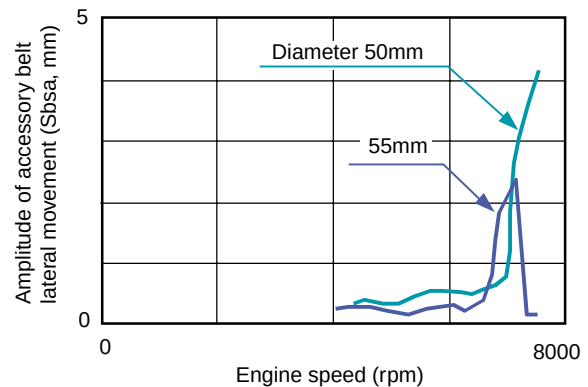


Fig.23 Effect of journal diameter size increase on accessory belt lateral movement

#### Design parameters for belt lateral movement in an engine

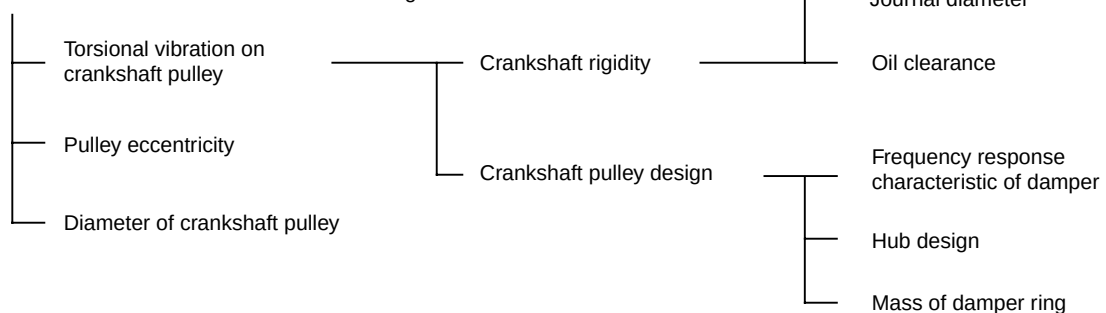


Fig.21 Design parameter tree

## 5. Conclusion

The authors established a laser sensor-based method for measuring and quantifying accessory belt behavior and elucidated the mechanism of a belt running off of the pulley by measuring belt movement and belt input, and by performing belt vibrational mode simulation, thus determining the following:

1. Phenomena leading up to accessory belt running off of the pulley
  - (1) Resonance occurs when the accessory belt's natural frequency equals 1/2 of the frequency of belt length fluctuation in the belt tension direction, said fluctuation caused by crankshaft torsional vibration.
  - (2) A correlation exists between belt lateral movement and belt length fluctuation in the belt tension direction, with the belt running off of the pulley when the threshold value is exceeded.
  - (3) Vibration in the lateral direction occurs as the accessory belt itself has a natural vibrational mode for lateral movement.
2. Achievements made possible by an understanding of the phenomena
  - (1) A "graph for use in judging the limit at which the belt runs off of the pulley" was created.
  - (2) Simulation of an accessory belt running off of the pulley was devised as a design tool.
  - (3) The above was shown to be effective in preventing the belt from running off of the pulley by improving design parameters for engine crankshaft components.

## 6. Acknowledgments

For their assistance with this research, the authors wish to express their appreciation to Mr. Hajime Maeda and Mr. Kenji Nakajima of the Tochigi R & D Center.

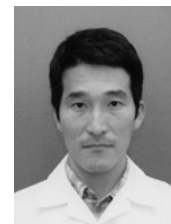
## References

- (1) Osamu Taniguchi: *Kaitei Shindou kougaku*, Corona Publishing Co., Ltd., Tokyo, p.130-132(1985) (Written in Japanese)

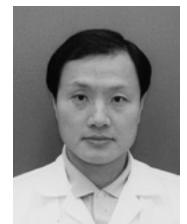
■ author ■



Atsuo FUJII



Shougo YONEMOTO



Kazuma OKUDA



Kiyoshi MIYAZAKI



Hiroshi MIYAZAWA



Seiji FURUMATA