

Evaluation Condition for Auxiliary Belt Tension Fluctuation in Engine Bench Test

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ABSTRACT

In order to evaluate the reliability of an auxiliary belt system consisting of a Poly-V belt and the auxiliary equipment driven by that belt, it is necessary to measure belt tension fluctuation that becomes an input load to the auxiliary component parts. This study proposes an example of a measurement method, clarifies the conditions that increase belt tension fluctuation in the actual use condition, and describes the engine running condition when substituting the actual vehicle running condition with an engine bench. The proposed measurement method enables measurement with the engine in the actual vehicle condition, and does not require changes to the auxiliary belt layout. Strain gauges are adhered to the auxiliary part adjacent to the span where the maximum belt tension fluctuation occurs, and the strain due to the belt tension fluctuation at that position is measured. The measured strain is then converted to the belt tension fluctuation using the calibration equation of belt tension and strain. In order to substitute actual vehicle tests with evaluation by engine bench tests, it is necessary to apply the running condition that results in the maximum belt tension fluctuation as the measurement condition. This requires measurement in the engine starting and compressor on/off conditions, which are transient conditions unique to an actual vehicle, in addition to the condition in which the engine speed is increased at the engine full load plus auxiliary maximum load.

1. Introduction

Many recent engine models use serpentine drive that drives multiple auxiliary equipment with a single belt. The driven AC generator (ACG) and air conditioner compressor have enhanced their efficiency over the years, but driving loads are increasing in order to further enhance automotive comfort. In addition, increased combustion excitation force due to higher combustion efficiency, together with weight reduction around the crankshaft (CS), is increasing the CS angular velocity fluctuation, which is a factor increasing belt tension fluctuation. As a result, auxiliary belt tension fluctuation is increasing, and the loads input to each auxiliary part via the belt are also increasing. To help ensure the reliability of auxiliary belt system component parts under harsh actual use conditions, it is necessary to accurately measure and verify the maximum value of the belt tension fluctuation that becomes these input loads.

Thus far, the reliability of auxiliary belt system component parts has ultimately been verified in the actual vehicle condition. However, demands to front-load engine development have made it necessary to create the specifications in the engine development stage before starting actual vehicle tests. Therefore, it is necessary to understand belt tension fluctuation occurring in an actual vehicle, and to evaluate this belt tension fluctuation by

engine bench tests.

This study proposed an example of a method for measuring belt tension fluctuation, clarified the conditions that increase belt tension fluctuation in the actual use condition, and investigated proper engine running conditions in order to evaluate auxiliary belt tension fluctuation by engine bench tests.

2. Auxiliary Belt System

2.1. Auxiliary Belt System Reliability

The auxiliary belt system refers to the series of functional part groups consisting of the Poly-V belt, the ACG, compressor and other auxiliary equipment driven by that belt, and the belt auto tensioner.

Auxiliary belt system reliability is verified by first measuring and checking the stress with S-N diagrams as the parts durability certification of each component part, and then durability is evaluated in the assembled engine state. In all cases, reliability verification should use the maximum value of the belt tension fluctuation that is the source of the load received by each component part.

2.2. Belt Tension Fluctuation

Friction drive-type auxiliary belts apply the set tension for transmission of the driving force by pressing the driving

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surface against the pulley surface as shown in Fig. 1. For this reason, the tension of each span is maintained uniformly at the set tension in the engine-stopped condition. However, when the engine is operated, the tension fluctuates due to the CS rotation fluctuation, the moment of inertia, and load of the auxiliary equipment (Fig. 2). This fluctuation of the tension in the engine-running condition is called belt tension fluctuation.

Belt tension fluctuation is amplified by the resonance of the auxiliary belt system, and in some cases can result in excessive tension that damages the auxiliary component parts.

The forced vibration model is generally expressed by the model shown in Fig. 3(a). When this model is applied to the auxiliary belt system, the external forced vibration force generated by the CS angular velocity fluctuation is $f_0 \sin \omega t$, and the inertia mass I of the ACG pulley can be expressed by a model consisting of an auxiliary belt comprising the spring constant k and the viscous damping constant c (Fig. 3(b)). In addition, when the natural frequency of the auxiliary belt system matches the forced vibration frequency ω , resonance occurs in the auxiliary belt system. The maximum amplitude occurs at this time, and the phase lag becomes $\pi/2$ ⁽¹⁾⁻⁽³⁾.

Figure 4 shows the CS and ACG pulley velocities when the belt tension fluctuation is increased by resonance. This shows that the ACG pulley velocity phase is delayed by approximately $\pi/2$ relative to the CS pulley velocity, and it can be confirmed that the auxiliary belt system is in the resonance zone and the belt tension fluctuation increases. This condition is referred to hereafter as auxiliary belt system resonance.

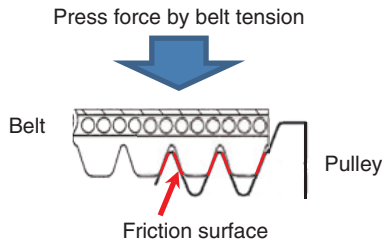


Fig. 1 Friction transmission of auxiliary belt

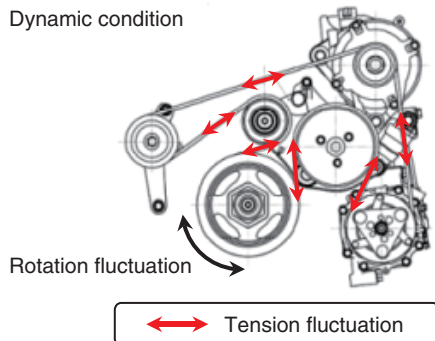
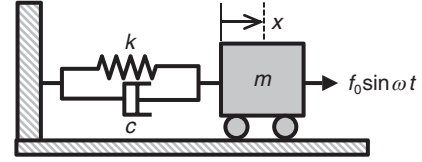


Fig. 2 Auxiliary belt tension fluctuation

Conversely, when a one-way clutch⁽⁴⁾ is mounted on the ACG pulley and the natural frequency of the auxiliary belt system is offset from the forced vibration frequency of the CS pulley to suppress resonance, the CS and ACG pulley velocity fluctuation become in-phase and belt tension fluctuation is reduced as shown in Fig. 5.

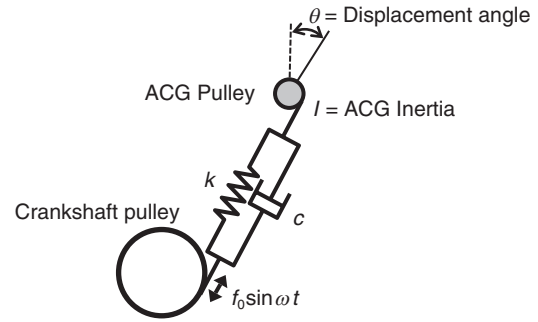


Equation of motion

$$m \frac{d^2 x}{dt^2} = -c \frac{dx}{dt} - kx + f_0 \sin \omega t$$

c : Viscous damping constant $f_0 \sin \omega t$: Forced vibration k : Spring rate m : Weight x : Displacement

(a) General model of forced vibration



(b) Auxiliary belt system forced vibration model

Fig. 3 Forced vibration model

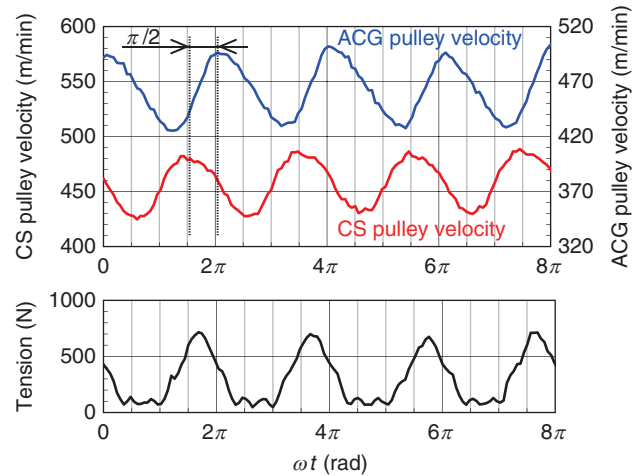


Fig. 4 Auxiliary belt tension fluctuation in belt system resonance zone

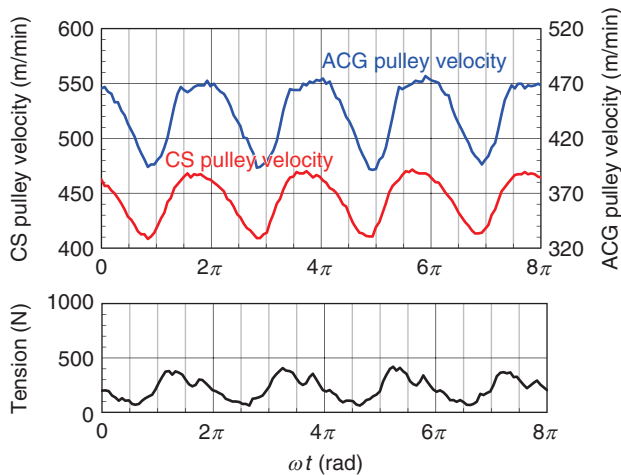


Fig. 5 Auxiliary belt tension fluctuation in belt system non-resonance zone

In addition, belt tension fluctuation also increases under transient operating conditions where the auxiliary load fluctuates.

3. Measurement Method

3.1. Belt Tension Fluctuation Measurement Position

Belt tension fluctuation occurs in all spans, but is the highest before the CS pulley (immediately upstream from the direction of rotation), where all of the auxiliary loads are added. When auxiliary belt system resonance occurs, the resonance is added to the tension in each span, but the position where the maximum tension is generated does not change. Therefore, the maximum tension in the belt layout shown in Fig. 6 is generated between the CS pulley and the water pump (WP), so the tension in that position (red arrows in Fig. 6) was measured.

3.2. Load Cell Creation Method

A known general method of measuring auxiliary belt tension fluctuation is to set a load cell pulley that outputs bending stress in the center of the span where the belt tension is to be obtained. In order to measure belt tension fluctuation in the actual use condition, it is necessary to set the load cell in the condition with the engine mounted in an actual vehicle. However, it is often a challenge to set a load cell given the space constraints in an actual vehicle. Therefore, this study employed a method that uses strain gauges to make an auxiliary component part that does not require special space into a load cell. Strain gauges were adhered to the WP housing to make the WP into a load cell in order to measure the tension between the CS pulley and the WP pulley, which is the position where the maximum tension is generated. The belt tension fluctuation was measured as the WP bending reaction shown in Fig. 6. No machining was performed to grind the ribs and reduce stiffness in order

to increase the sensitivity, and the original shape was maintained. Two strain gauges each were adhered to the base of the WP housing ribs at the tensile position and the compression position as shown in Fig. 7(a). In addition, a bridge circuit that connects the opposing strain gauges was configured as shown in Fig. 7(b) to simultaneously increase the sensitivity and cancel the apparent output due to temperature change.

3.3. Load Cell Calibration Method

Next, the method of converting the strain output of the WP load cell into the auxiliary belt tension fluctuation is described. The WP with strain gauges adhered was assembled into the engine used for measurement, and a jig capable of generating arbitrary tension that can be substituted for the auxiliary belt auto tensioner (AT) was set

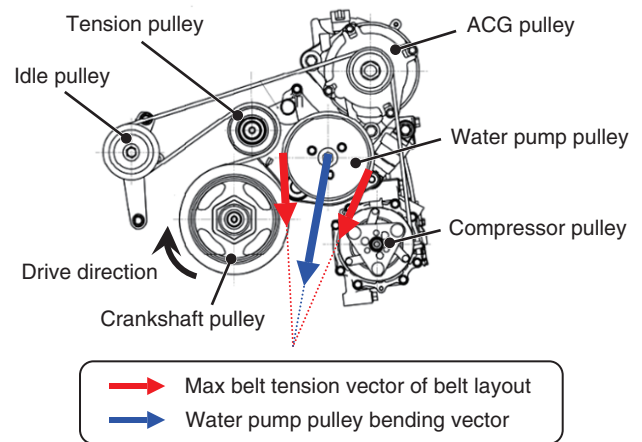


Fig. 6 Auxiliary belt layout of tension fluctuation measuring engine

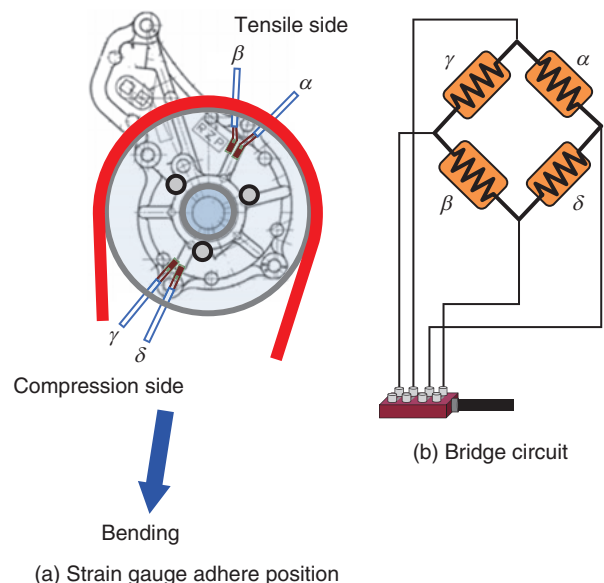


Fig. 7 Water pump load cell-making method

as shown in Fig. 8. The set tension of the belt was varied by rotating the hexagon nut in the center of the jig. The tension was obtained from the vibration frequency when the span between the ACG and the idler was flicked in the engine-stopped condition, and the calibration line was obtained from the relationship between the tension and the strain output at that time.

Figure 9 shows the relationship between the belt tension and the WP housing strain. The belt tension has a directly proportional relationship with the WP housing strain, and the belt tension fluctuation was calculated by multiplying the strain generated on the WP housing with the calibration line slope.

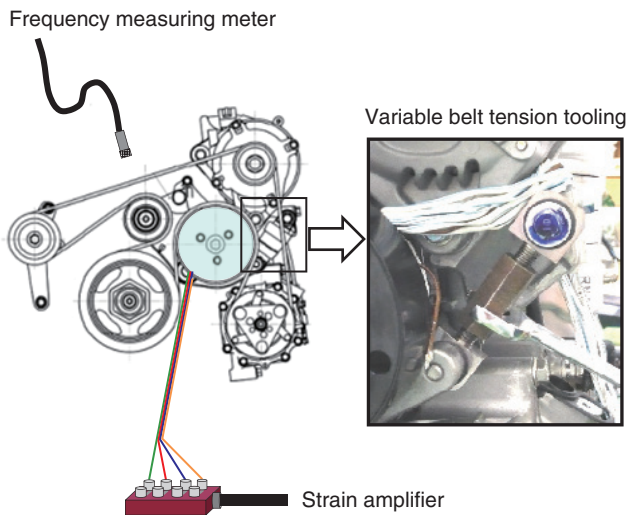


Fig. 8 Variable belt tension tooling and belt set tension measuring by span frequency at static condition

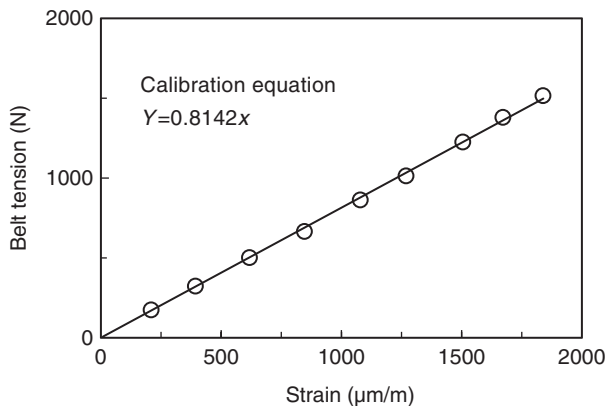


Fig. 9 Static calibration line between belt tension and water pump load cell strain

4. Test Conditions

4.1. Engine Specifications

The auxiliary equipment specifications may differ according to the vehicle, even when the engine uses the

Table 1 Measuring engine specifications

Part	Specification
Engine	Higher crankshaft angle acceleration engine of same belt layout engine series
Transmission	Lower crankshaft axis inertia of all transmission applications For firing engine bench, lockup clutch tight condition
Auxiliary belt	Belt length lower tolerance
Auto tension	Spring force higher tolerance Damping force higher tolerance
AC generator	Higher volume of same belt layout engine series
Compressor	Higher refrigerating capacity of same belt layout engine series

Table 2 Engine and auxiliary load conditions of firing bench

Equipment	Load type		Condition
Bench	Engine load		Continuous full load
	Auxiliary load	AC generator	Continuous full load
		Compressor	Continuous full load

same type of engine block as the frame. Therefore, the specifications that result in the highest belt tension should be selected when measuring belt tension fluctuation.

Table 1 lists the items related to engine specifications that increase belt tension fluctuation. Measurement used the auxiliary belt system shown in Fig. 6, with each item in Table 1 set so as to increase belt tension fluctuation. Engine and transmission specifications were selected that result in high CS rotational fluctuation, which is a source of auxiliary belt tension fluctuation. Auxiliary belt system specifications were selected that increase the belt set tension to the tolerance upper limit, and also increase the maximum tension. Auxiliary load specifications were selected that result in high driving torque and increase the driving transmission force of the belt.

4.2. Running Conditions

The maximum belt tension in the auxiliary belt system resonance condition was measured using engine bench tests. Measurement was performed in the running mode where the engine speed is increased from the lowest speed at which the throttle can be fully opened up to the maximum output engine speed in approximately 30 s. Next, an actual vehicle was used to investigate whether there are any conditions under which the maximum belt tension in the resonance condition is exceeded due to transient running conditions in the actual use condition.

Table 2 lists the load conditions used to obtain the maximum belt tension in the resonance condition on the

Table 3 Engine and auxiliary transient load conditions

Equipment	Load Type		Condition
Vehicle	Engine Load		Engine start
			Put in gear
			Racing
			Shift change
			Torque converter stall condition
	Auxiliary Load	AC generator	On-Off
		Compressor	On-Off

engine bench. The engine load was the maximum load that results in the maximum CS rotation fluctuation. The auxiliary load was the maximum load that results in the maximum driving torque. This mode in which the engine speed is increased at the maximum engine and auxiliary loads is referred to hereafter as the continuous load condition.

Table 3 lists the conditions hypothesized to increase belt tension during transient conditions in an actual vehicle; that is to say, in the actual use condition. First, the running conditions were extracted that involve a change in velocity that increases the belt tension on both the drive-side CS pulley and the driven-side auxiliary pulleys. Next, these running conditions were sorted into factors deriving from engine loads and auxiliary loads.

5. Test Results

5.1. Continuous Load Condition Tests Using an Engine Bench

Figure 10 shows the results of measuring the belt tension fluctuation on an engine bench using an engine with the specifications listed in Table 1, under the continuous load conditions listed in Table 2. This shows that large resonance tension originating in the torque fluctuation due to combustion occurred in the low-engine-speed range of 2000 rpm or less. Conversely, the range of 2000 rpm or

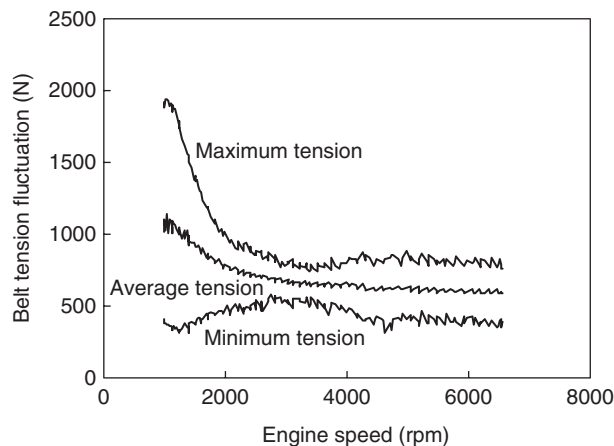


Fig. 10 Belt tension fluctuation of continuous load condition in firing engine bench

more was outside the resonance zone, so the belt tension fluctuation stabilized at a lower level.

5.2. Transient Running Condition Tests in the Actual Use Condition

The specifications listed in Table 1 were assembled into an actual engine, and the belt tension fluctuation was measured under each transient condition listed in Table 3. These results were then compared with the results obtained in the continuous load condition (Fig. 10) to verify the need to add each transient condition to the engine bench running conditions.

5.2.1. Engine starting

Figure 11 shows the belt tension fluctuation at engine start. Combustion starts after cranking, then the engine speed rises and the peak tension occurs partway to the first idle state, after which the belt tension fluctuation drops.

Figure 12 shows the relationship between the CS pulley

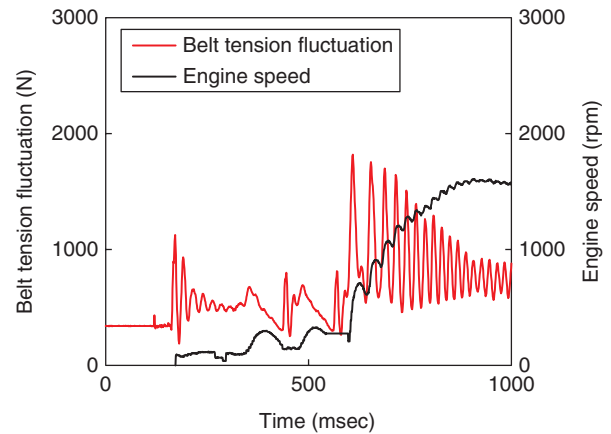


Fig. 11 Auxiliary belt tension fluctuation at engine start

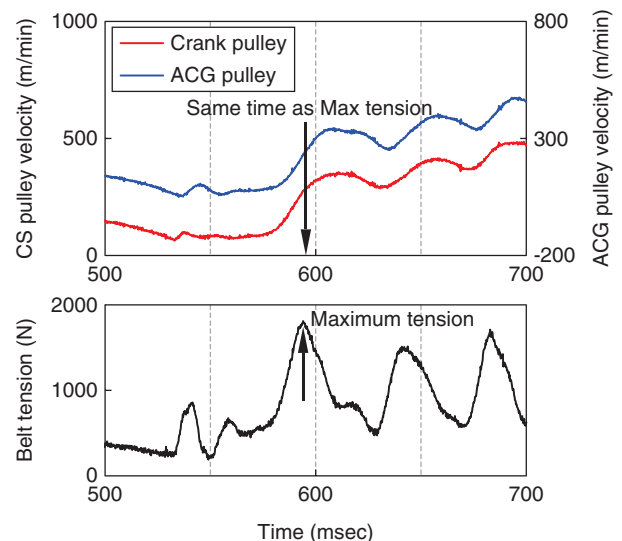


Fig. 12 Relation between belt tension fluctuation and pulley velocity

and ACG pulley velocities when the belt tension fluctuation rises immediately after engine start. The initial tension peak near 2000 N is synchronized with the rise in the CS pulley velocity, and it is thought that the maximum tension was generated as the force to increase the rotations of all driven auxiliary equipment. In addition, the rise in the CS pulley velocity matches with the ACG pulley velocity phase, indicating that auxiliary belt system resonance does not occur.

Figure 13 compares the tension peak at engine start with the engine bench test results (Fig. 10). The tension peak exhibits a high value at engine start, even though there is no auxiliary load. In addition, there is no auxiliary belt system resonance and belt tension is generated by only CS acceleration, so the generating factors differ from the maximum belt tension in the continuous load condition. Therefore, the engine starting condition should be added to the continuous load condition for evaluation.

5.2.2. Putting in gear

Figure 14 shows the belt tension fluctuation when the transmission select lever is changed to the D position

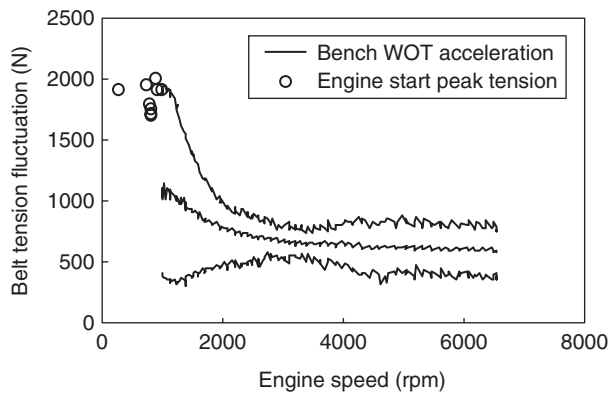


Fig. 13 Belt tension comparison between peak belt tension at engine start and bench continuous load condition

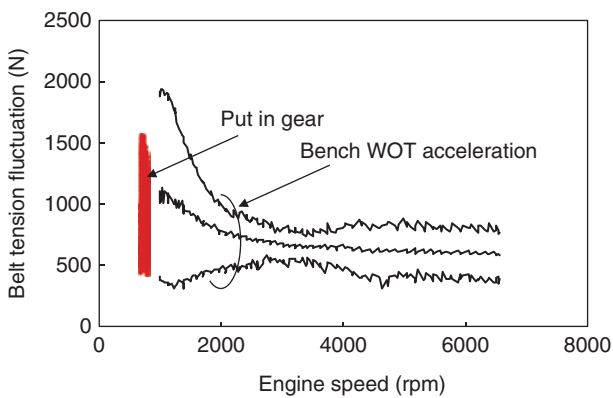


Fig. 14 Belt tension fluctuation comparison between putting in gear position and bench continuous load condition

from the condition with the full electrical load and air conditioning load applied during idle operation with the transmission in the neutral position. This operation to change the gear from neutral to the D position is hereafter referred to as putting in gear.

In order to maintain the idle engine speed with respect to the auxiliary load and the drive system loads such as the torque converter, the engine control system increases the intake manifold pressure, which increases the CS rotation fluctuation. In addition, the idle engine speed is within the auxiliary belt system resonance speed zone (Fig. 10), so the belt tension fluctuation increases. However, the continuous load condition on the engine bench performs engine full-load operation from near the idle engine speed, so the belt tension fluctuation is higher than when putting in gear. This means that the putting in gear condition is included in the continuous load condition, so there is no need to add it to the engine bench evaluation conditions.

5.2.3. Racing

Figure 15 shows the time series measurement results of the belt tension fluctuation and the change in engine speed when racing is performed.

Compared to the belt tension fluctuation due to auxiliary belt system resonance at the idle engine speed, both the engine load and the belt tension fluctuation increased the instant the throttle was opened, but the tension then dropped when the engine speed rose above the resonance zone.

Figure 16 arranges the belt tension fluctuation results in Fig. 15 according to the relationship with the engine speed, and compares it with the results in the continuous load condition on the engine bench. In the racing condition, auxiliary belt system resonance occurred in the same low-speed range as in the continuous load condition. However, the engine speed rises above the resonance zone before the engine full load is reached in the low-speed range where resonance occurs. As a result, the belt tension fluctuation in the racing condition is lower than that in the continuous load condition, so there is no need to add it to the engine bench evaluation conditions.

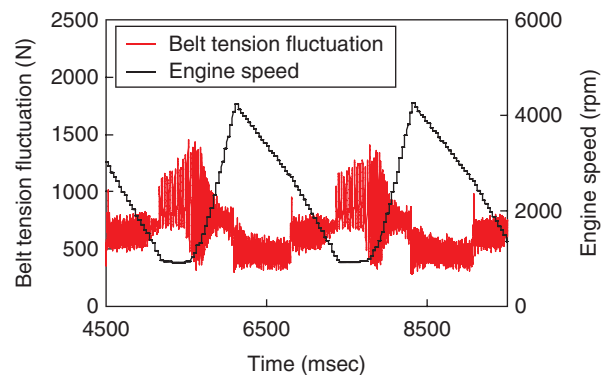


Fig. 15 Belt tension fluctuation and engine speed at racing condition

5.2.4. Shifting

The belt tension fluctuation was confirmed when accelerating and shifting in a CVT vehicle. Figure 17 shows these results. No influence whatsoever of CVT shifting was confirmed, and the tension fluctuation resembles that during the continuous load condition on the engine bench. However, in the actual use condition the torque converter absorbed the CS rotation fluctuation in the low-engine-speed range, so the belt tension fluctuation did not increase compared to the engine bench test condition. This means that belt tension fluctuation in the shifting transient condition is included in the continuous load condition, so there is no need to add it to the engine bench evaluation conditions.

5.2.5. Torque converter stall

Figure 18 shows the belt tension fluctuation when the transmission select lever is changed to the D position, the accelerator pedal is pressed while stepping on the brake until the throttle is fully open, and the output is absorbed by the torque converter. This running condition is referred to hereafter as torque converter stall.

The accelerator pedal was pressed until the throttle is fully open, so the engine load increased, but the engine

speed rose to the torque converter stall speed, so the low engine speed could not be maintained with the throttle fully open as in the continuous load condition, which resulted in a low maximum tension. This means that the belt tension fluctuation in the torque converter stall condition is included in the continuous load condition, so there is no need to add it to the engine bench evaluation conditions.

5.3. Auxiliary Load Transient Condition Tests using an Actual Vehicle

The auxiliary belt tension fluctuation when auxiliary loads are applied to an actual vehicle in a transient manner was measured to confirm whether there is a difference from that in the continuous load condition, and it was verified whether these conditions can be included in the continuous load condition.

5.3.1. ACG load

Figure 19 shows the belt tension fluctuation and the ACG load when electric loads such as the headlights and rear defogger are applied in succession. The ACG load rises as the electric equipment part switches are turned on, and at the same time the belt tension fluctuation also increases.

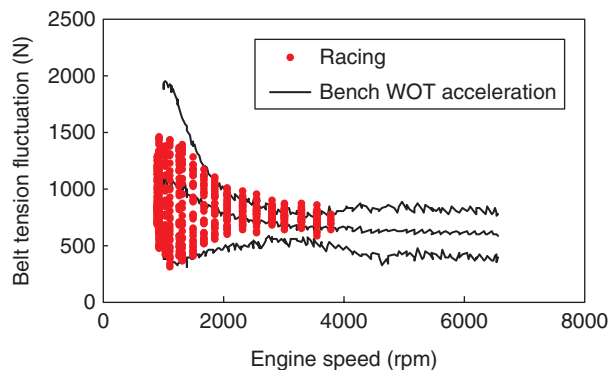


Fig. 16 Belt tension fluctuation comparison between racing and bench continuous load condition

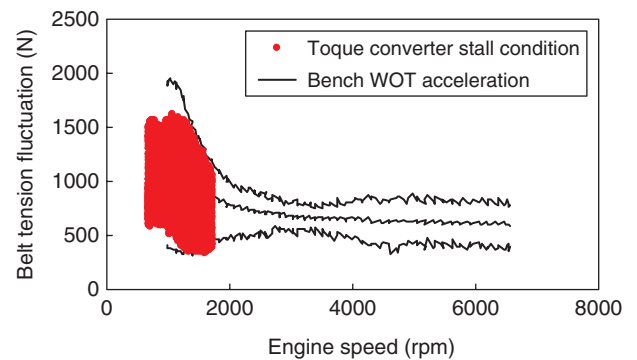


Fig. 18 Belt tension fluctuation comparison between torque converter stall condition and bench continuous load condition

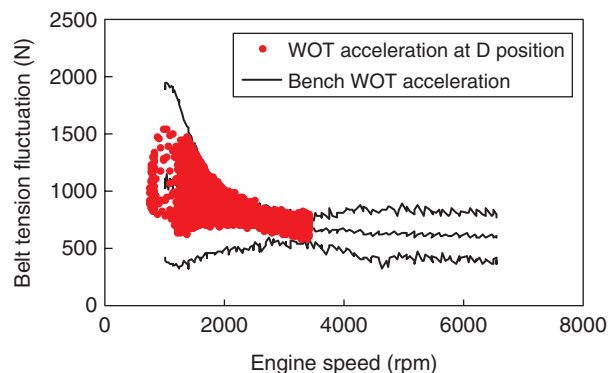


Fig. 17 Belt tension fluctuation comparison between WOT acceleration at select lever drive position and bench continuous load condition

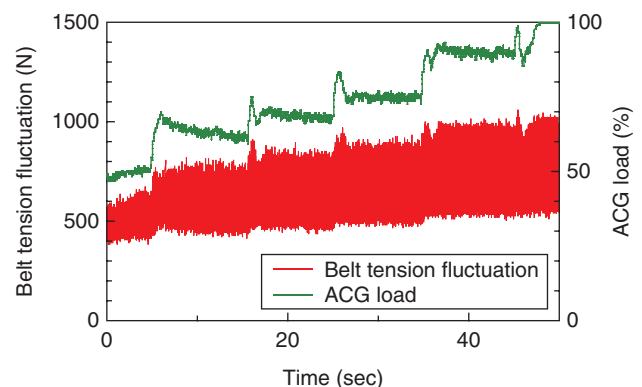


Fig. 19 Belt tension fluctuation and ACG load when ACG load rises in succession

Figure 20 shows the relationship between the fluctuation amplitude peak value on the high tension side of the belt tension fluctuation shown in Fig. 19 and the ACG load. This shows that the ACG load and maximum belt tension fluctuation value are correlated, and that the belt tension fluctuation did not have a peak value due to the transient manner that applied the ACG load.

The belt tension fluctuation changes according to the amount of the ACG load, but it does not change according to the manner in which the load is applied. Therefore, the condition with the maximum electric generation load results in the largest ACG load, and that condition is the same as the continuous load condition.

5.3.2. Compressor load

Figure 21 shows the belt tension fluctuation when the compressor switch is turned on and off. The belt tension rose and indicated a peak when a load was applied, but then dropped instantly thereafter. This is because the compressor is accelerated from a velocity of zero to the crankshaft velocity the instant the clutch is engaged, so the work to accelerate the compressor appears as belt tension.

Figure 22 shows the results of comparing the peak tension at compressor on/off with the continuous load condition. The peak tension in the high-engine-speed range

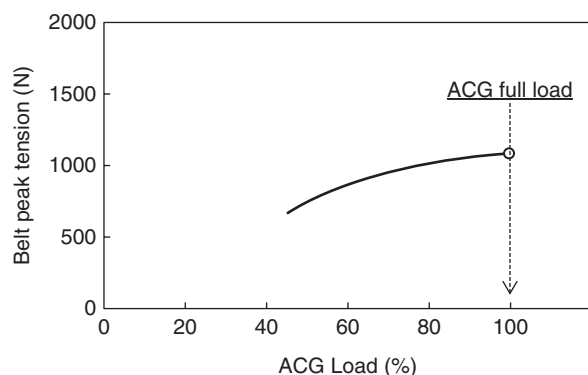


Fig. 20 Relation between belt peak tension and ACG load

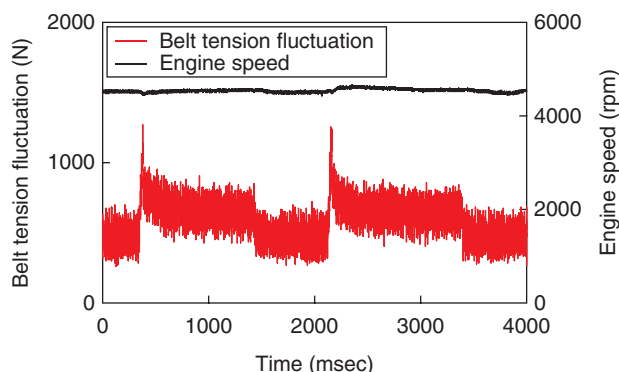


Fig. 21 Belt tension fluctuation at compressor clutch engage

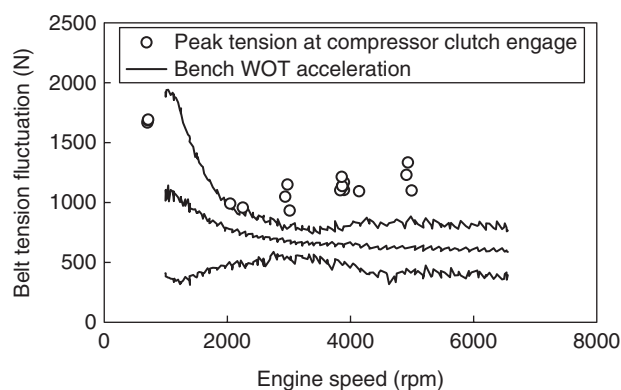


Fig. 22 Belt tension comparison between peak belt tension at compressor clutch engage and bench continuous load condition

exceeds that in the continuous load condition, and this difference became noticeable at engine speeds of 2000 rpm or more that are outside the auxiliary belt system resonance zone. This shows that the peak tension at compressor on is generated by a different factor than that for tension fluctuation due to auxiliary belt system resonance, and cannot be included in the continuous load condition. Therefore, the compressor on/off running condition should be added to the engine bench test.

6. Conclusion

In order to evaluate auxiliary belt system reliability, an example of a belt tension fluctuation measurement method was proposed, and the engine running conditions and auxiliary load conditions were clarified that enable evaluation of an auxiliary belt system in the actual use condition by engine bench tests.

(1) Belt tension fluctuation measurement method

A method was proposed to enable measurement of belt tension fluctuation using an engine in the actual vehicle condition, without changing the auxiliary belt layout. This method adheres strain gauges to the auxiliary part adjacent to the span where the maximum belt tension fluctuation is generated, to enable use as a substitute load cell.

(2) Running conditions used to measure belt tension fluctuation

The engine starting and compressor on/off conditions are transient conditions unique to actual vehicles. When evaluating belt tension fluctuation by engine bench tests, these transient conditions should be added to the running condition that increases the engine speed in the continuous load condition, which consists of the engine full load and maximum auxiliary load.

References

- (1) Watari, A.: Forced vibration, Kikaishindou, Maruzen publishing CO., LTD., p. 103-107 (1966) (in Japanese)

- (2) Sakata, M.: Vibration of degree-of-freedom, Forced vibration, Hadoutoshindounokougaku, Kyoritsu shuppan CO., LTD, p. 53-59 (1980) (in Japanese)
- (3) Meirovitch, L.: Forced vibration of single-degree-of-freedom system, Elements of vibration analysis, Burein tosyō CO., LTD., p. 39-46 (1984)
- (4) Sato, K., Mikuriya, I.: Compact Clutch Integrated Pulley for Alternator, NTN Technical Review, No. 75, p. 123-127 (2007) (in Japanese)

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