

Research on ISG Belt Drive System for Idling Stop System

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ABSTRACT

To enable a belt-drive Integrated Starter Generator (ISG) to be used in an idle stop system, the belt system must be capable of both driving the accessories and starting the engine. Accomplishing this with a conventional belt system required an increase in the tension of the belt, which also increased friction losses and is thus incompatible with the intention of increasing fuel economy.

Testing quantified the effect of the increased belt tension on increasing friction losses. With this knowledge the research team focused on the auto-tensioner mechanism and the design of a superior belt system without the requirement for an increase in tension. Belt tension was reduced through the employment of an auto-tensioner in which contraction can be controlled by exploiting the incompressibility of fluid and by modifying the belt layout to enable optimal positioning of the new auto-tensioner. The use of reverse torque was tested and proven to be an effective method of further reducing the tension of the belt. The combination of these innovations has resulted in the development of a superior belt system well matched to the requirements of an idle stop system.

1. Introduction

The Kyoto Protocol of the United Nations Framework Convention on Climate Change became effective in February 2005, thus mandating the signatory nations to reduce their carbon dioxide emissions. As shown in Fig. 1, the emission of carbon dioxide in Japan in 2004 exceeded the targeted value for 2008 by 14%. Demands are being placed on the automobiles, which accounts for a significant percentage of emissions, to further increase fuel economy. An idling stop system can promptly achieve enhanced fuel economy.

Utilization of an idling stop system that uses a belt-driven Integrated Starter Generator (ISG) requires a belt system that is able to drive the engine accessories including ISG, and also start the engine. In the conventional auto-tensioner belt system which

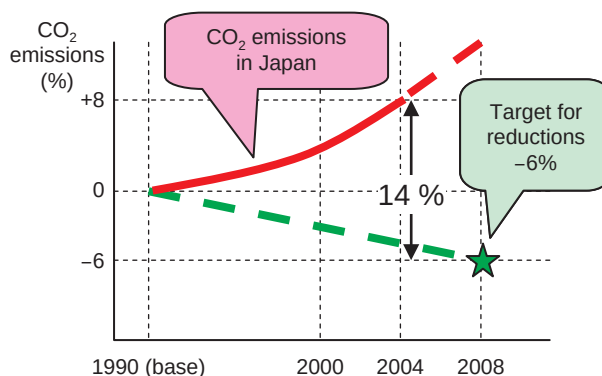


Fig. 1 Status of CO₂ emissions and target for reductions in Japan

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uses a single belt to drive several accessories, the auto-tensioner would be pushed back when the engine starts, causing the belt to slacken. This requires the tension to be set higher during starting conditions. Research was conducted on a new auto-tensioner mechanism and belt layout that enabled the mechanism to be mounted in the optimum location, and also to determine an ISG control method for engine starting. As a result of this study, the above-mentioned issues have been overcome. This paper describes the configuration and operation of the system, in addition to the results of engine starting tests.

2. ISG Drive and Auto-tensioner Issues

2.1. Auto-tensioner Layout Issue

The optimum mounting position of an auto-tensioner, for driving accessories only, was found to be on the belt segment just behind the crank pulley, along the running direction of the belt at which the set tension can be minimized. When the engine was being started by the ISG, a significantly larger tension than that generated during normal accessory drive was generated between the crank pulley and the ISG, along the running direction of the belt. This caused the belt to elongate, while on the opposite side the reverse phenomenon had occurred. It was possible to increase the tension on the overall belt by shortening the portion of the belt over which high tension was applied, and by minimizing the difference in length resulting from the belt elongation and contraction. The optimal position of the ISG was found to be just behind the crank pulley as an accessory along the running direction of the belt⁽¹⁾. Figure 2 shows the combined optimum positions of the auto-tensioner and

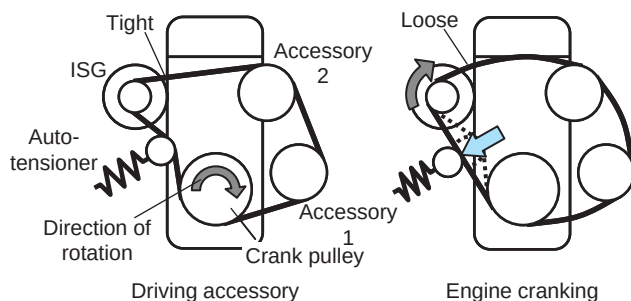


Fig. 2 Issue of auto-tensioner

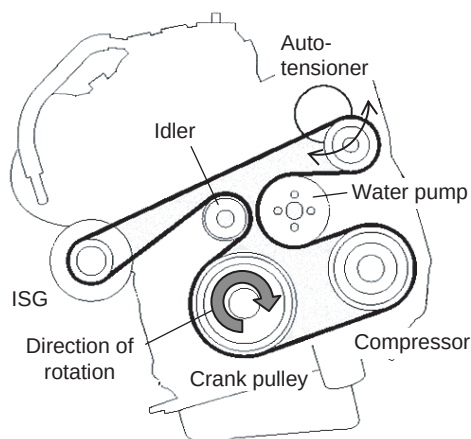


Fig. 3 Example of previous ISG system configuration

the ISG as a single layout.

These positions were found to be optimum for driving the accessories, but when the engine was being started by the ISG, the tension generated by the ISG caused the auto-tensioner to be pushed back, reducing the overall tension on the belt. As a result, it was not possible to obtain adequate friction, so there was the possibility of slippage occurring^{(2), (3)}. In order to prevent this phenomenon, it was necessary to raise the tension setting of the auto-tensioner to a value higher than that of the generated tension. However, this increased belt tension during normal accessory driving, so there remained the issue of the durability of the belt itself, and of the accessory bearings.

2.2. Conventional Solution and Tension Issue

Figure 3 shows a practical example of the layout of the ISG and auto-tensioner which was intended as one solution for this issue^{(4), (5)}. Normally, when the engine is being started, the belt segment, just behind the ISG in the direction of the belt motion, loses tension. The auto-tensioner pulls up the segment, maintaining the belt tension on the slack side, which is important in transmitting friction. This position was found to be optimum for driving the engine⁽²⁾.

On the other hand, because the auto-tensioner had been moved away from its optimum position for driving the accessories, it was necessary to set tension higher. In other words, it was necessary to superimpose the maximum effective tension required to drive the ISG^{(2), (3)}, while it generates electricity, on the set tension of the auto-tensioner, which results in the tension being greatly increased. Thus with this solution as well, high tension remained an issue.

3. Friction Loss and Tension Accompanying the Accessory Belt Drive

3.1. Friction Loss Testing Equipment

The belt tension should be set to the minimum value necessary to enable the belt to transmit drive force, and it was expected that any tension greater than this level will increase power loss of the bearings to which the tension is applied. However, concrete knowledge and information concerning the ratio of the loss related to the belt drive, to the whole power loss of the engine friction, and the relationship between the increase in belt tension and friction loss could not be obtained from past publications.

Because the reduction of belt tension was an issue, it was necessary to obtain an accurate understanding of the tension and its affects. A test was completed to measure the belt friction using the test apparatus shown in Fig. 4.

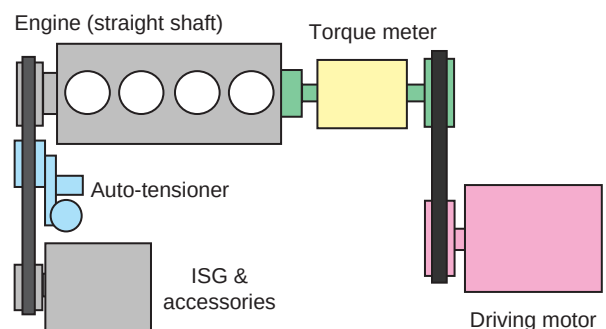


Fig. 4 Equipment for belt friction measurement

The accessories and the belt layout of the test engine are shown in Fig. 8 of the next section. The original crankshaft was replaced with a round, straight bar and the engine crankcase consisted of the crank journal alone, with the connecting rods and pistons removed. The chain that drives the camshaft was removed so that the crankshaft drove only the belt mounted accessories via the crank pulley. A torque meter was used to measure the friction loss torque generated by the belt drive, including that of the crank journals. One end of the torque meter was attached to the flywheel side of the crankshaft, and the input end was driven by a driving motor via the belt. The friction loss power was calculated from the product of this torque and the rotational speed.

3.2. Friction Loss Test Conditions and Results*

In order to make the temperature conditions of the engine and each bearing the same as those of a warm engine, the engine oil temperature was raised by the heat of motoring.

In order to understand the effect of tension on friction loss torque, the tension was set to two values: the necessary amount for conventional accessory drive, and to the original amount plus a 40% increase. The measurements were performed over the entire engine speed range. Also, in order to measure the friction loss of the crank, the test was repeated with the accessory belt removed. The results are shown in Fig. 5.

Figure 6 shows the results of calculating the ratio of increase of the friction torque due to increased tension to the whole engine friction which was measured in advance.

According to the measured results, the friction loss torque related

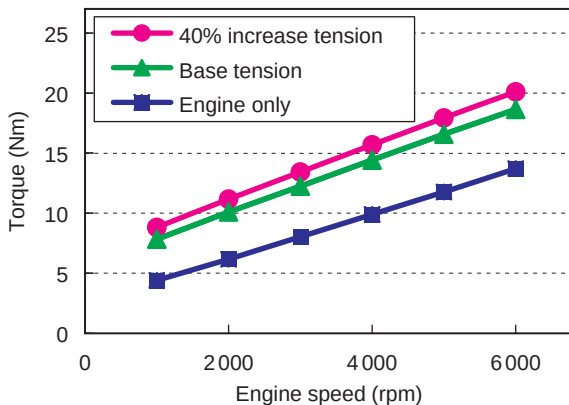


Fig. 5 Increase in friction torque due to increased tension

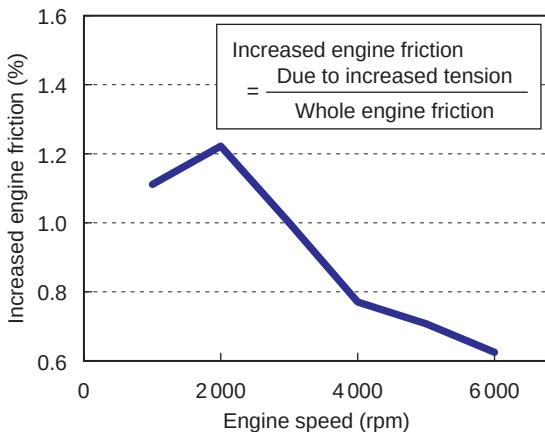


Fig. 6 Influence of increased tension

to the belt drive on the high tension side at 1 000 rpm accounted for about 50% of the entire friction loss. As the rotational speed increased, the belt drive friction loss increased. However the increase in the friction loss of the crank journal also became larger, and at 6000 rpm accounted for about 30% of the entire loss.

The increase in the friction loss torque of the belt drive due to the increase in belt tension was a maximum of 12.5% at low rotational speeds, and 8% at high rotational speeds.

The ratio of the friction loss (due to the increase in belt tension) to the friction loss of the whole engine is in the range of 1.2% to 0.6%. At low engine speeds, which are in the normal engine speed region, the ratio exceeds 1%.

While the engine was running, friction loss due to the increase in belt tension occurred unavoidably, regardless of the running conditions, resulting in a corresponding increase in fuel consumption.

Also, because the crankshaft bore has journal bearings, which are generally force-lubricated by an oil pump, the starting torque from standstill, in which the oil pressure is zero, is directly affected by the belt tension, causing it to increase. From the engine starting aspect as well, the increase in tension is a detrimental factor.

Because any increase in the belt tension has an adverse affect both on the fuel consumption when the engine is running, and on engine startability, the necessity of reducing the belt tension in an idling stop system can be recognized significantly.

4. Belt-driven System that Uses an HLT (Hydraulic Locking Tensioner)

4.1. HLT Mechanism and Layout of Accessories

A solution to the issue of the layout of Fig. 2 that permits the lowest tension to be applied while driving accessories, which is almost the entire driving period, is sought from a new viewpoint: an automatic-tensioner. An auto-tensioner must be capable of elongating and contracting freely, to maintain the belt tension, and it must incorporate a means of suppressing contraction due to the increase in belt tension when the engine is being started. In order to meet these conflicting requirements, we focused on a new mechanism that could suppress contraction. In the mechanism, a damping force due to the flow of fluid accompanying the mutual elongation and contraction of the cylinder and the piston is generated, and by closing the flow path, it was possible to utilize the incompressibility of the fluid shut in the cylinder. Specifically, in the construction employed, a solenoid valve for opening and closing the fluid path was installed on an auto-tensioner that provided a damping force generated by shearing of the oil.

Figure 7 shows the construction of an HLT (Hydraulic Locking Tensioner), and Fig. 8 shows the layout of the accessories including the HLT. In the HLT, the cylinder is installed on the tensioner pulley side, and the piston on the engine side, and a coil spring generates a repulsive force against contraction. When the HLT elongates, oil is drawn into the cylinder through a check valve at the bottom of the cylinder. When it contracts, the oil flows out through an orifice in the piston, thus generating a damping force. When the solenoid is energized, the valve mounted on the piston closes, shutting the oil in the cylinder and thus enabling the contraction of the piston to be suppressed.

Even in this condition, oil can flow into the cylinder enabling the piston to elongate, due to the repulsive force of the spring. As a result, the function that applies tension to the belt is maintained, permitting optimization of the belt tension for driving accessories

and for engine starting, which were issues with earlier conventional systems.

4.2. Verification of the Effectiveness of the HLT

4.2.1. Belt behavior testing equipment

To enable the engine to be started by the belt of an ISG system, it was necessary to understand the various factors that are related to the transmission of torque by friction. The method used to measure the belt pulley tension involved converting the strain at the support shaft into tension. The tension on the taut side when the engine is being started was measured using an idler, and the tension on the slack side was measured by installing an additional idler, between the crank pulley and the compressor.

In order to study the frictional transmission between the belt and the pulley, it was necessary to determine the running speeds of the ISG pulley, the crank pulley, and the belt, respectively. Accordingly, the surface speeds of the back of the belt, and the points on the side of the ISG and crank pulleys where the surface speed must be equal to that of the back of the belt, were measured using a laser Doppler vibration meter which permits non-contact, highly accurate speed measurements. The elongation and contraction of the HLT were measured by installing a stroke sensor between the fixed end and the free end, on the arm side. Also, a microphone was installed in the vicinity of the belt, and the slip of the belt was checked from the noise emitted.

All of these signals were recorded by a single recording device

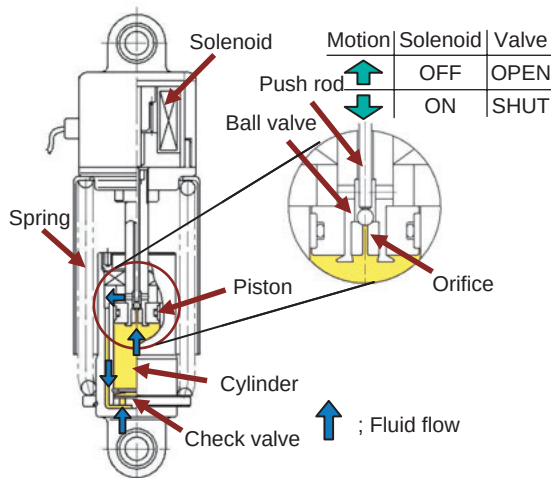


Fig. 7 Mechanism of HLT

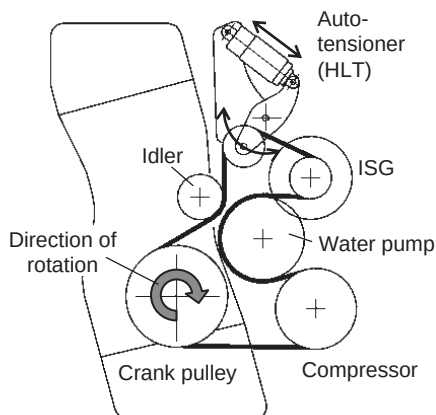


Fig. 8 Accessory drive layout with HLT

on the same time line, enabling the time correlation to be understood. Figure 9 shows the configuration of the measuring instruments. Figures 10 and 11 show the actual installation of the laser Doppler vibration meter and the microphone.

4.2.2. Performance of the HLT and engine starting results°

Figure 12 shows the results of actually using an HLT to start the engine. In order to clarify the performance of the HLT, the engine was also deliberately started without suppressing the contraction of the HLT, for comparison. The results are shown in Fig. 13. The engine was cranked by making the ISG generate the maximum torque from the commencement of starting. In the case

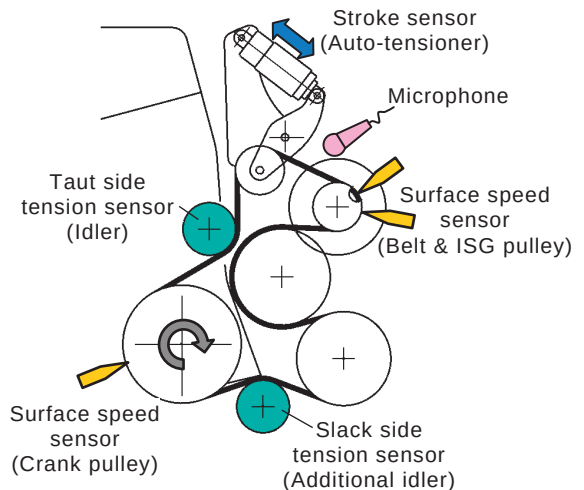


Fig. 9 Measuring instrument layout

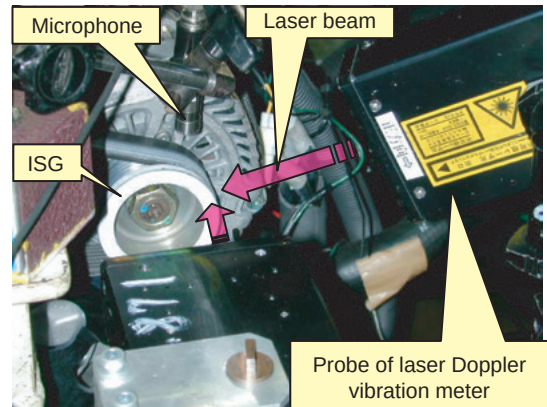


Fig. 10 Surface speed sensor for ISG

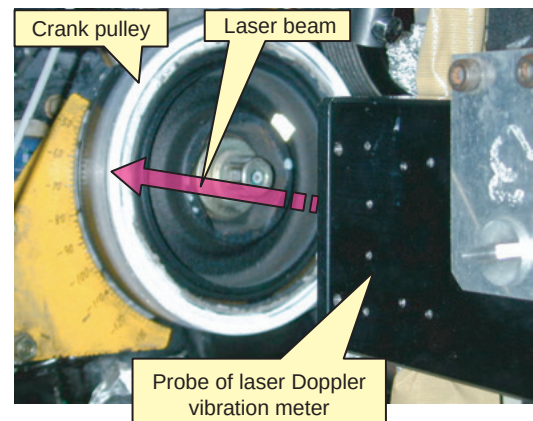


Fig. 11 Surface speed sensor for crank pulley

where contraction was not suppressed, the HLT contracted due to the belt tension on the taut side, the tension on the taut side fell rapidly, and the tension on the slack side became roughly zero. Because of this tension reduction, the frictional transmitting force between the pulley and the belt decreased, resulting in a difference in the speeds of the ISG pulley surface, the crank pulley, and the belt.

In other words, belt slippage occurred. The slip noise increased when the surface speed difference became large, thus verifying this phenomenon. In order to prevent excessively high rotational speeds, the ISG limits the drive torque at high speeds, which causes the surface speed of the ISG to exhibit sinusoidal wave behavior. It was presumed that if the drive torque had not been limited, the speed would have risen excessively.

Because of this slippage, almost no power was transmitted from the ISG to the crankshaft, and the engine failed to start.

On the other hand, when contraction control was performed, a small amount of contraction occurred in the HLT. However, the tension on the taut side and the slack side was symmetrical with respect to the initial tension level, thus ensuring that adequate effective tension for starting the engine was maintained. As a result, there was almost no discrepancy between the surface speed of the ISG and that of the crankshaft, and the engine was able to be started.

From these two results, it was possible to identify the various factors related to the starting of the engine. In addition, the function and performance of the HLT has clearly been confirmed.

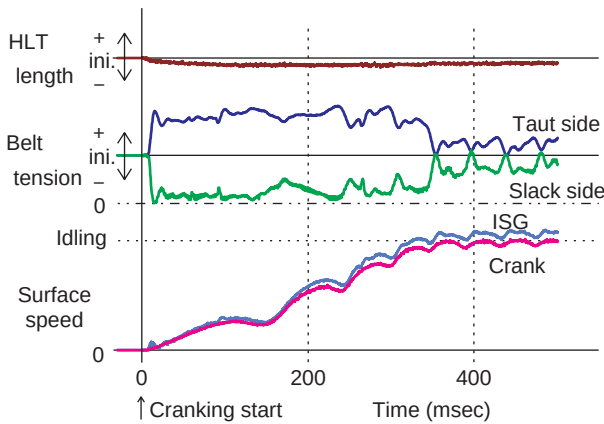


Fig. 12 Engine start with HLT locking

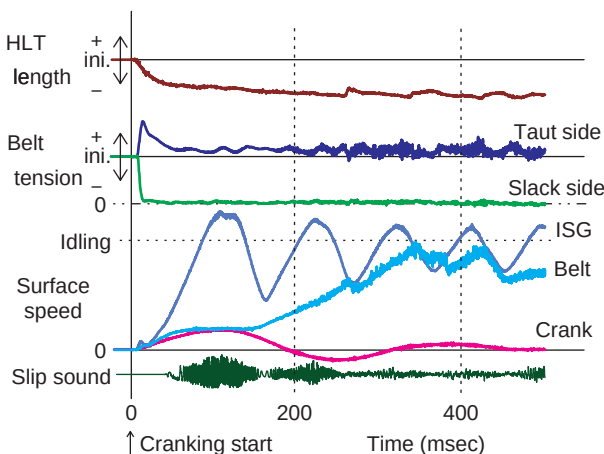


Fig. 13 Engine start without HLT locking

5. ISG Control at Engine Starting

5.1. Aim of ISG Reverse Torque Control

Engine starting necessitates a belt drive force that exceeds the maximum load to drive all of the accessories. It was confirmed empirically in the layout of the test engine accessories, including the HLT, that the tension on the taut side and the slack side would increase and decrease, respectively, by one half of the effective tension generated by the ISG. In order to maintain the frictional transmission on the belt, it was necessary to maintain the tension on the slack side, so it was necessary that the initial tension be at least one half of the effective tension as that of the ISG. This value was higher than the minimum necessary value for driving the accessories. Considering the load on the belt as well as the load on the bearings of each accessory and of the engine, it was desirable to set the initial tension to a lower value.

While searching for a method to set the initial tension to as low a value as possible, and to raise the tension immediately before starting the engine, a solution was found in the characteristics of the HLT and drive control of the ISG.

The HLT suppresses contraction as a result of the energization of the solenoid, however elongation can occur freely. When slackness occurs in the segment, it is always possible to maintain the tension. In this condition, if the ISG generates a torque that acts in the reverse direction to that of the torque generated when the engine is started, the segment on the HLT side will slacken, and the segment on the opposite side will become tauter. When reverse torque is generated for a minimum amount of time, the HLT elongates within the time, while the reverse rotation of the engine remains extremely small. When the reverse torque is released, the tension on the belt is increased by an amount corresponding to the elongation of the HLT. It is considered that if the ISG is caused to generate a forward torque immediately after this, the belt will be assisted by the increased tension, and will adequately transmit friction force, thus ensuring that the engine starts reliably.

5.2. Confirmation of the Performance of Reverse Torque Control

The following is a description of the results of starting the engine by combining the HLT with ISG control. In order to confirm the increase in tension due to reverse torque control, a test in which zero torque time was inserted into the interval during which the torque changes, from the negative direction to that of the forward torque, was also performed. Figures 14 and 16 show the torque command to ISG, and Figs. 15 and 17 show the results of engine starting. When the ISG generates reverse torque during time T_r indicated in Fig. 14, after the HLT performs contraction control, the HLT elongates in order to maintain the tension on the slack segment. The mean value of the tension on the taut and slack sides, which indicates the overall level of the tension, increases by about

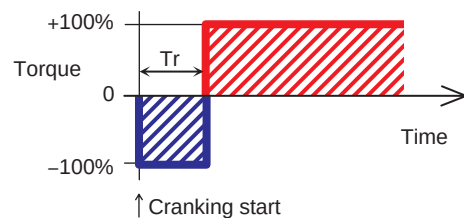


Fig. 14 Torque command for ISG

one half of the effective tension with respect to that of the initial value. Next, the engine commences to start as a result of the forward torque. Though the HLT contracts by a small amount, the tension was maintained during this process. Because of the high tension, an adequate frictional transmission force was obtained, and the engine was started under a condition in which the difference in the surface speed of the ISG and the crankshaft was smaller than that for the case where HLT contraction suppression alone was used.

In the results (Fig. 17) of the starting test carried out using the torque commands indicated in Fig. 16, a reverse torque was applied for a period of T_r , then the torque was made zero for a period of T_i , after which a forward torque was applied.

After the convergence of the tension fluctuation due to the removal of the reverse torque, it was possible to confirm an increase in tension with respect to the initial value, which was of the same order as that obtained in the previous test on the taut and slack sides, thus verifying the performance of this control method.

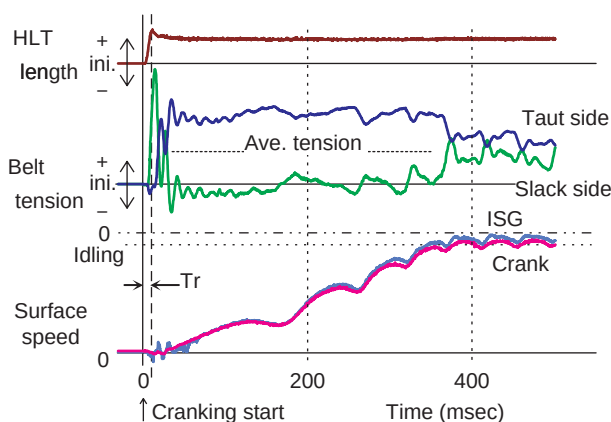


Fig. 15 Engine start with reverse torque

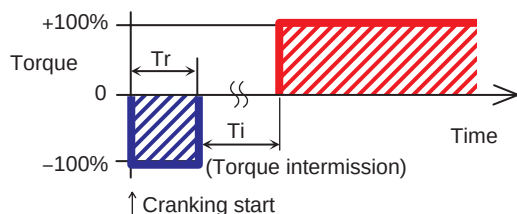


Fig. 16 Torque command with intermission

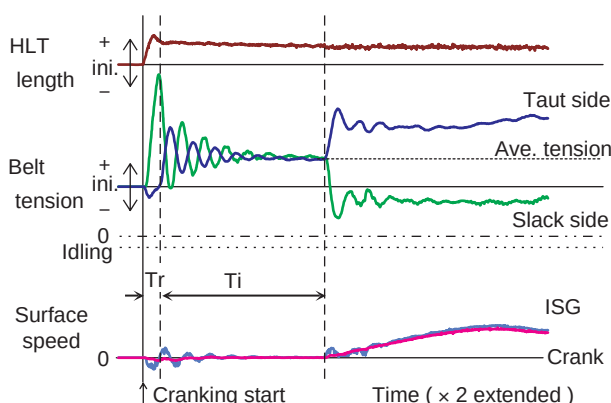


Fig. 17 Engine start with reverse torque and intermission

As described above, by applying reverse torque control from the ISG, it was possible to increase and maintain the tension, including that on the slack side, thus confirming that this is an effective method of reducing the initial tension setting.

6. Conclusion

- (1) Research was carried out on a belt drive system including an HLT, and as a result, the different requirements of driving the accessories and starting the engine were understood.
- (2) It was found possible to greatly reduce the initial tension setting by combining the characteristics of the HLT with ISG control.
- (3) A detailed measurement of the behavior of the various factors related to engine starting was performed, and the results obtained verified the effectiveness of HLT and ISG control.
- (4) The friction loss due to the belt tension was clarified empirically, and thus the necessity of reducing the tension was also clarified.

The results of the research performed by the authors enabled the issues of tension in the ISG belt drive system to be resolved. The development of this ISG and HLT belt system can considerably reduce torque loss by stopping the engine instead of idling it, and also by maintaining a minimum amount of belt tension. Both of these enhancements to the belt system will enhance fuel economy.

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