

Research on Noise Reduction for Pinion Shift-type Starters

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ABSTRACT

The mechanism that generated of noise was analyzed and research on noise reduction was conducted in pinion shift-type starters for idle stop systems. Both pinion shift noise and cranking noise are components of the noise generated during engine start; vehicle tests demonstrated that cranking noise is produced for a longer period and causes greater discomfort to driver and passengers, and countermeasures were therefore devised against this form of noise. Bench tests revealed that gear whine was a more significant factor in cranking noise than gear rattle, and countermeasures therefore targeted this source of noise. The spur gears conventionally used in pinion shift-type starters were replaced by helical gears and the contact ratio was increased, reducing noise by 7 dB. When establishing gear specifications, analyses of stress in the sections making contact were conducted to enable judgment of the ease with which damage occurs to gear end faces during pinion gear shifting. The relation between angle and stroke of the pinion gears during shifting was optimized to achieve superior shift performance.

1. Introduction

Idle stop systems, which automatically shut off the engine when a vehicle idles at traffic lights, etc. are being increasingly employed as a means of reducing emissions of the greenhouse gas CO₂. Various methods are used to restart the engines of vehicles provided with these systems. The majority restart the engine instantaneously using a high-power electric motor, as in the hybrid cars shown schematically in Figs. 1-a and 1-b. The use of high voltages increases the cost of these systems. The system shown in Fig. 1-a positions the motor between the engine and the transmission, while the system in Fig. 1-b locates the motor on a separate shaft. This positioning increases the width of these systems (by the width of the motor and the belt

respectively), making it difficult to fit them in the engine compartment.

Figure 1-c shows a system employing a conventional pinion shift-type starter to restart the engine. These systems are lower in cost than those discussed above, and are employed in comparatively less expensive vehicles with low displacement engines and manual transmissions. However, because these systems are very loud when starting the engine, noise reduction measures are required to enable them to be fitted in idle stop vehicles, in which the engine is constantly stopped and restarted. The project discussed in this paper therefore analyzed the mechanism that generated noise in pinion shift-type starters and conducted research on methods of noise reduction to develop a less expensive, low-noise idle stop system.

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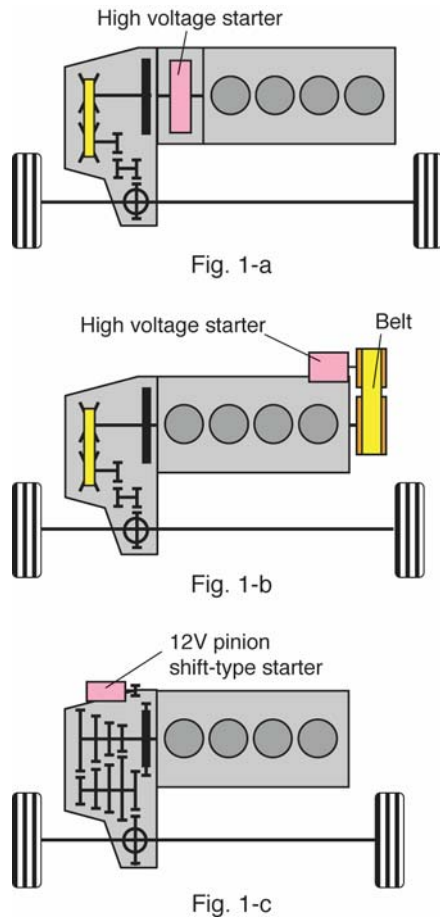


Fig. 1 Starter types for idle stop system

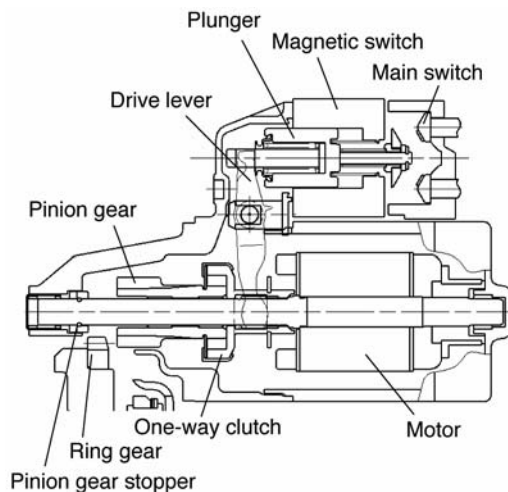


Fig. 2 Pinion shift-type starter

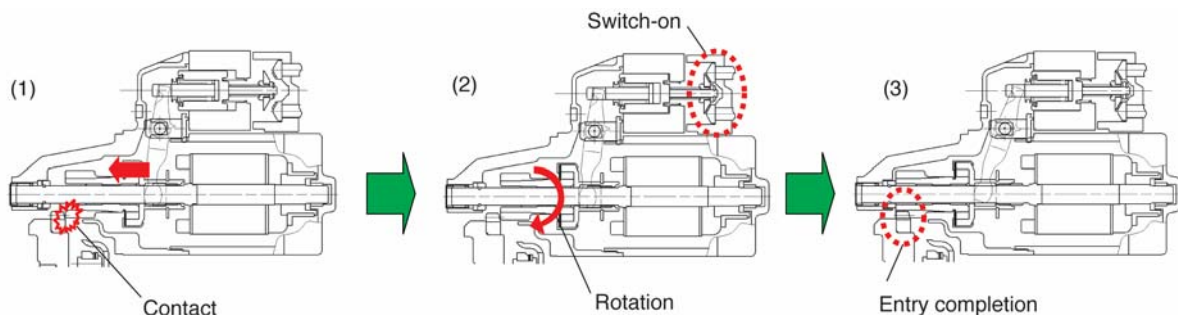


Fig. 3 Operation of pinion shift

2. Analysis of Noise at Engine Start

Figure 2 shows the configuration of the pinion gear shift-type starter used in this research. Spur gears are employed in pinion gear shift-type starters to reduce costs. The operation of this type of system is shown in Fig. 3. (1) The command to start the engine causes current to flow to a magnetic switch, which in turn draws in a plunger. The pinion gears are connected to the plunger by the drive lever. The movement of the plunger pushes the pinion gears towards the ring gears, and they strike the end faces of the ring gears. (2) The closure of the main switch causes battery voltage to be transmitted directly to the motor, rotating the pinion gears. (3) The rotation of the pinion gears causes them to mesh with the ring gears. The pinion gears are pushed farther into the ring gears until they completely mesh and the engine is cranked.

Figure 4 shows changes in the level of cabin noise during engine start over time. Noise during engine start is composed of pinion shift noise generated as the pinion gears shift to the ring gears, and cranking noise generated by the meshing of the pinion and ring gears when shifting is completed and the starter motor drives the engine. The noise level of cranking is low in comparison to that of shifting, but it is produced for a longer period, and tests demonstrated that it therefore causes occupants of the vehicle a greater level of discomfort. This research project therefore restricted its focus to the reduction of cranking noise.

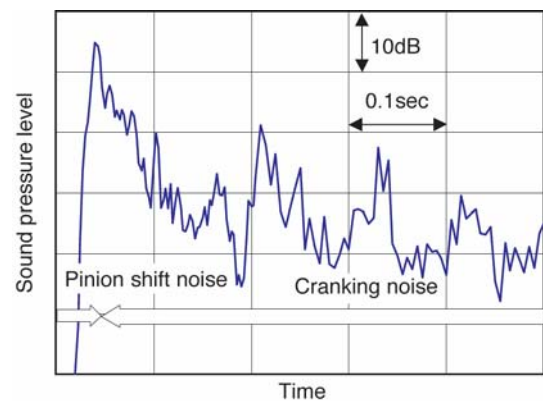


Fig. 4 Cabin noise during engine start

Figure 5 shows changes over time for engine speed (N_e) and starter motor speed multiplied by the reduction gear ratio between the pinion gears and ring gears (N_m') during

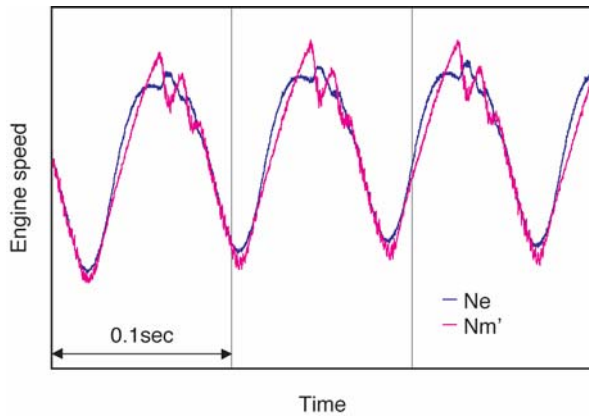


Fig. 5 Engine speed and starter motor speed during engine start

cranking. Engine speed fluctuates periodically during cranking. An almost complete cycle is shown in Fig. 6. Figure 7 shows motor torque over the same cycle, and Fig. 8 shows longitudinal vibration of the vehicle in the starter motor. In Fig. 7, there is a time zone during which the starter motor is not driving the engine, and torque is close to zero. This corresponds to time zone 1, from a to b, in Fig. 6. During this period engine speed exceeds motor speed. In time zone 1, the pinion gears are driven by the ring gears, and the opposite tooth surfaces, which are not in contact when the pinion gears drive the ring gears, are in contact with the surfaces. During this period the one-way clutch is over-running. Time zone 2 is represented by b to c in Fig. 6. During this period, backlash is reduced in the pinion gears because the motor speed exceeds the engine speed. Finally, at c, the pinion gear drive side tooth surfaces and the ring gear driven side tooth surfaces make contact, generating gear rattle.

As can be seen from Fig. 8, after c, when the starter motor is generating torque, i.e., driving the engine, there is a higher amount of vibration than when it is not driving. This vibration is gear whine generated by the mesh of the gears, and is dominant over gear rattle.

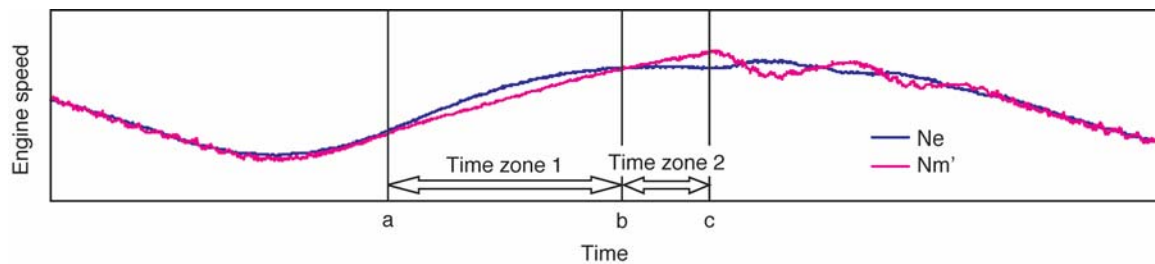


Fig. 6 Engine speed and starter motor speed during engine start

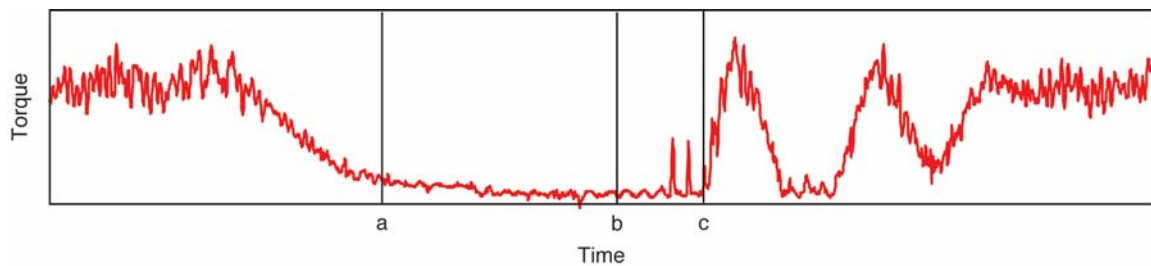


Fig. 7 Torque produced by the starter motor during engine start

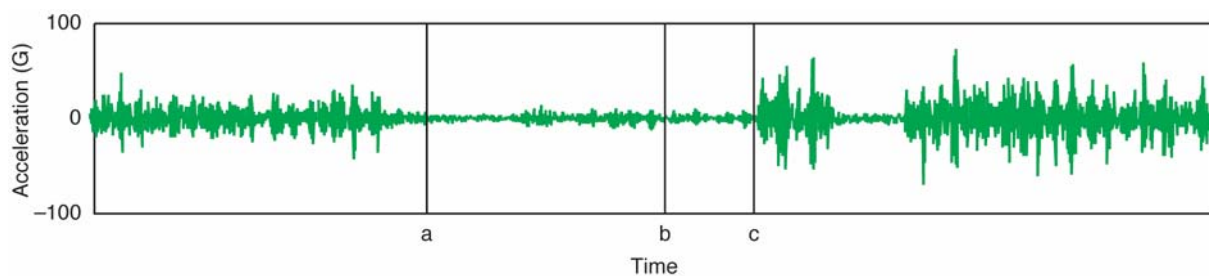


Fig. 8 Vibration of starter during engine start

3. Analysis of Cranking Noise

To analyze cranking noise, tests were first conducted on a test stand to determine the relationship between gear tooth profile, backlash, gear contact width, contact ratio, and gear whine. Gear specifications producing superior results in these tests were then evaluated in a test vehicle. As Fig. 9 shows, for tests on the test stand the pinion gears and ring gears were meshed in advance, and the behavior of each section of the gears and the amount of noise generated was measured with the starter motor driving.

3.1. Tooth Profile

To determine the effect of improving the tooth profile on cranking noise, tests were conducted using two types of ring gears with different profiles, and noise levels were compared. The 'spur gear' column in Table 1 shows the specifications of the gears, and Table 2 shows the results of measurements for the different tooth shapes driven by the starter motor. A in Table 2 is a mass-produced tooth profile, while B represents

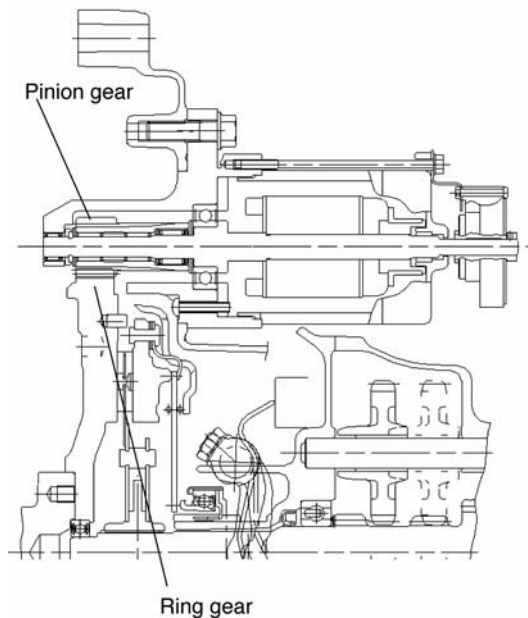


Fig. 9 Constant mesh type starter motor

Table 1 Gear specifications

Item	Total contact ratio	Normal module	Helix angle (deg.)	Contact width (mm)
Spur gear	1.09	2.54	0	9
Helical gear	1.25	2.5	4	9
	1.45	2.25	12	9
	1.80	2.25	28	9
	1.84	2	20	9
	1.91	1.75	20	9
	1.97	2	28	9
	2.33	2	20	18.7
	2.39	2.25	28	18.7
	2.45	1.75	20	18.7
	2.64	2	28	18.7
	2.68	2.25	36	18.7
	3.62	1.5	36	18.7

an improved profile over the mass-produced model. The figures for waviness represent the highest value obtained from measurements of four teeth; other figures are averages. It is clear from a comparison of the maximum figures for waviness and the averages for profile slope deviation and helix slope deviation that the tooth profile of gear B is more accurate than that of gear A.

Figure 10 shows the results of test stand measurements of sound pressure level during cranking. There is only a 0.5 dB difference between the sound pressure levels for tooth profiles A and B, demonstrating that improving the tooth profile is largely ineffective in reducing cranking noise.

Table 2 Teeth profiles data

		Teeth profiles A		Teeth profiles B	
		Pinion gear	Ring gear	Pinion gear	Ring gear
Involute	Profile slope deviation	3.1	-4.3	2.3	8.7
	Bulge	-2.5	4.5	0.3	0
	Waviness of profile	9.2	19.6	1.6	1
	Tip relief	8.6	4.3	7	8.1
	Profile slope bias	-3.8	-4.3	-0.2	-0.7
Lead	Helix slope deviation	-7.5	-2.7	-2	5.1
	Crowning	-0.5	-3.2	4.9	5.3
	Waviness of helix	11.3	14	1.4	0.9

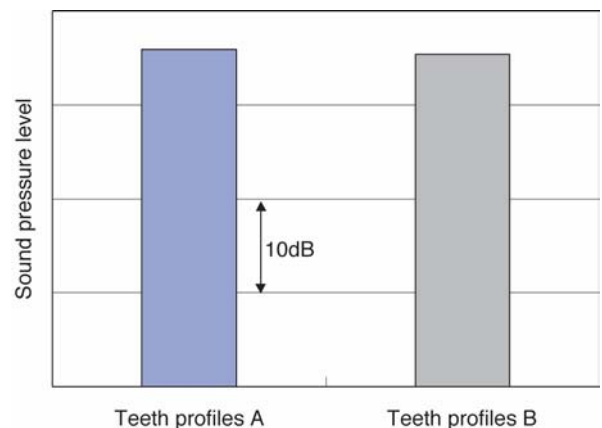


Fig. 10 Comparison of sound pressure level during engine start for different teeth profiles on test stand

3.2. Backlash

Next, to determine the effect of gear rattle, a gear with variable backlash was constructed, and cranking noise was compared. The specifications of the gears remained the same, as shown in Table 1 (spur gear); only backlash was varied from 0.15 mm to 0.45 mm in 0.1 mm increments. The results of test stand measurements of cranking noise are shown in Fig. 11. As shown there, the lowest measurement for cranking noise was taken at a backlash of 0.35 mm. When backlash is small, power transmission causes the teeth to deform, and the tooth surfaces on the side that is not driving contact each other, and when backlash is large, gear rattle

increases. Test results demonstrated that the minimum cranking noise is generated at specific levels of backlash, but these levels match backlash settings in mass-produced gears, and adjustment of backlash is therefore ineffective as a noise reduction measure.

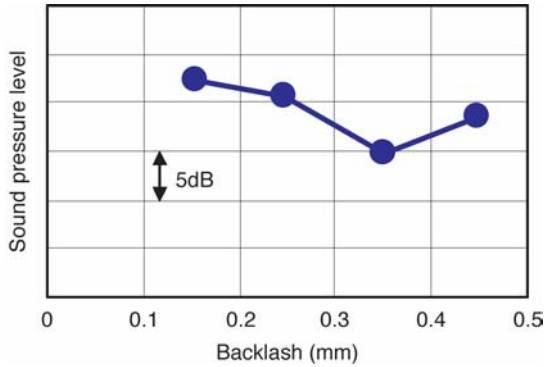


Fig. 11 Relationship between backlash and noise level of engine cranking on test stand

3.3. Gear Contact Width

Tests were conducted with gears of the same specifications to determine the effectiveness of increasing contact width in reducing cranking noise. As Fig. 12 indicates, the sound pressure level during cranking decreases as contact width increases. This is thought to be because increased flexural rigidity of the teeth reduces the amount of deformation occurring at power transmission. However, increasing the contact width in the vehicle required making the stroke longer during pinion gear shift, increasing the cost and weight of the starter. Increasing the contact width could therefore not be considered an effective method of reducing noise. The next stage of this research therefore examined the effect on cranking noise of using helical gears to increase the contact ratio, enabling the amount of deformation of the teeth to be reduced without increasing contact width.

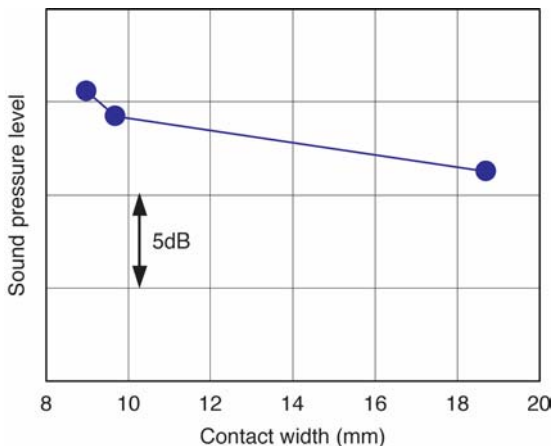


Fig. 12 Relationship between contact width and noise level of engine cranking on test stand

3.4. Gear Contact Ratio

Table 1 shows the specifications of the helical gears. The reduction ratio of the pinion gears and ring gears was set as

equivalent to that of the spur gears. As in the analyses of the spur gears, the pinion gears were meshed with the ring gears before noise tests were conducted. Figure 13 shows the results of test stand measurements of cranking noise. The results demonstrate that cranking noise is reduced by approximately 8 – 16 dB by increasing the contact ratio, but that the effect is small at a contact ratio of 2.5 and above.

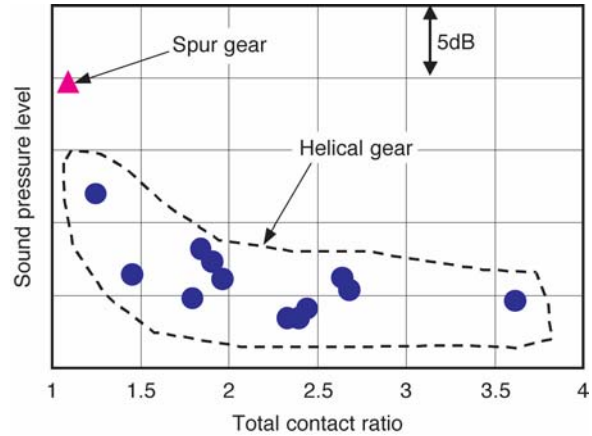


Fig. 13 Relationship between total contact ratio and noise level of engine cranking on test stand

3.5. Cranking Noise in a Vehicle Cabin

Having demonstrated in test stand tests that increasing contact ratio by utilizing helical gears is effective in reducing cranking noise, the project proceeded to vehicle testing. The specifications of the helical gears used in these studies were selected from Table 1. Figure 14 shows a comparison of the sound pressure level in a vehicle cabin when using mass-produced spur gears and helical gears, which increased the contact ratio to 1.84. In the test vehicle, increasing the contact ratio reduced cranking noise by 7 dB. A pinion gear shift-type starter was employed in the test vehicle. There were concerns that this would cause gear damage and rebounding during shift, therefore, gear specifications were established on the basis of the analyses described in sections 4 and 5.

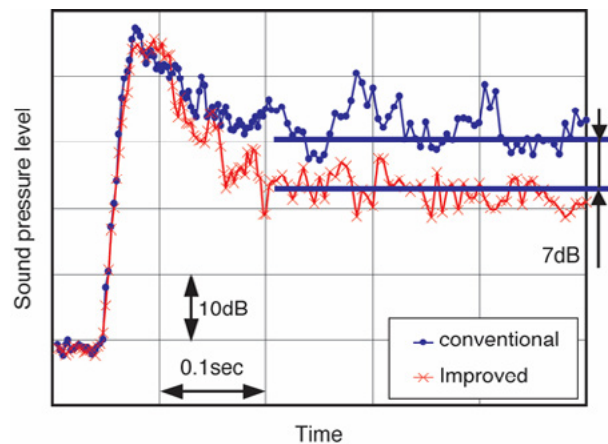


Fig. 14 Cabin noise during engine start

4. Analysis of Ring Gear Stress

The tests discussed above demonstrated increasing contact ratio to be the most effective method of reducing cranking noise. In practical terms, this involved reducing the size of the module to increase the number of teeth, and making the helix angle greater. Because this reduced the size of the gears and produced acute angles at the end faces, there were cases in which the end faces were damaged when the pinion gears made contact with the ring gears. The stress generated in the sections of the gears in contact was therefore analyzed using the finite element method. Figure 15 shows a pinion gear end face brought into contact with a fixed ring gear end face. The pinion gear was rotated until its drive side tooth surfaces made contact with the ring gear driven side tooth surfaces. This was taken to be a pinion gear angle of zero. The range of α in equation (1) from a pinion gear angle of zero was calculated. As Fig. 16 shows, the maximum stress was generated in the edge of the end face. Figure 17 shows the relationship between pinion gear angle and maximum stress on the ring gear. The stress generated in the ring gear increases as the pinion gear angle becomes smaller, because the area in contact decreases. No matter what specifications were tested, the end faces struck each other, causing plastic deformation. The rate at which the elastic limit was exceeded, t , is defined by equation (2). Gear specifications were selected using t as an indicator of end face damage.

$$\alpha = \frac{360}{Z} \quad (1)$$

$$t = \frac{\beta}{\alpha} \quad (2)$$

Z : Number of pinion gear teeth

β : Pinion gear angle at which elastic limit is exceeded

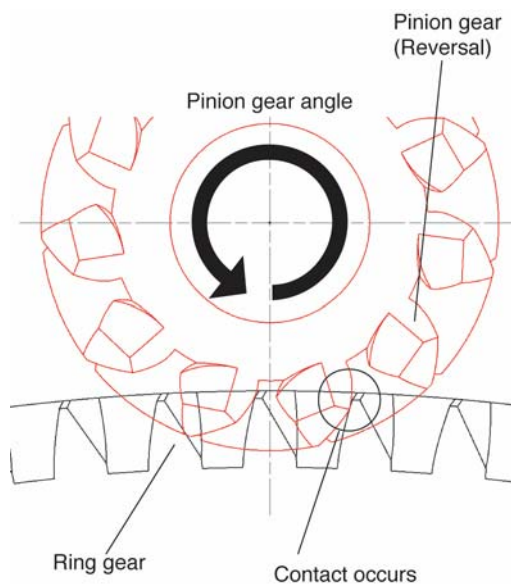


Fig. 15 Condition at pinion gear angle=0

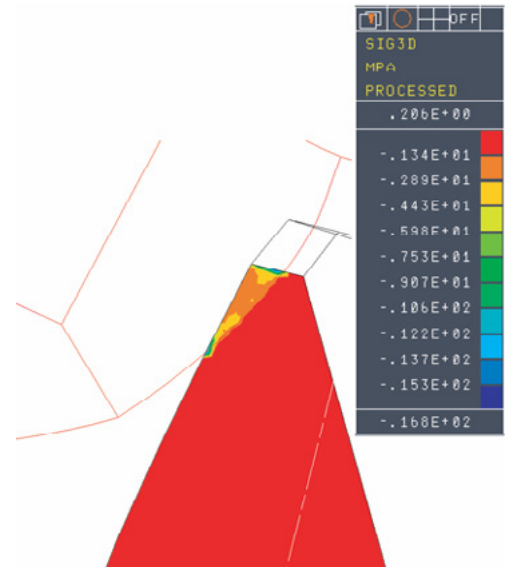


Fig. 16 Stress analysis results for ring gear

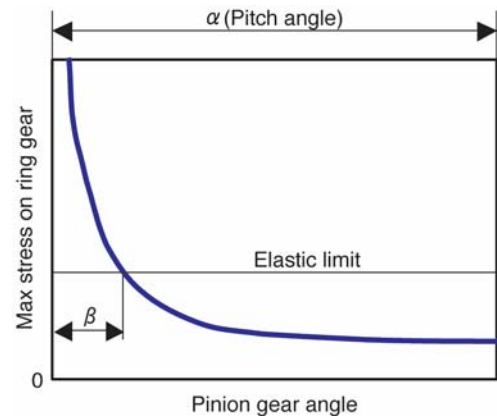


Fig. 17 Relationship between pinion gear angle and ring gear stress

5. Pinion Gear Shift Performance

The changes made to the specifications of the gears against mass production specifications, such as the size of the module and the helix angle, resulted in changes to the chamfering of the end face. These changes made the pinion gear unable to shift; the effect of pinion gear angle on stroke was therefore analyzed using mechanical system analysis software. Figure 18 shows the direction of pinion gear angle and stroke. Figure 19-a shows specification E, which was unable to shift, and Fig. 19-b shows the results of the analysis. It was determined that in this gear specification there was a certain range of angles during pinion gear shift (d in Fig. 19-b) at which the stroke did not increase even though the angle was increasing. This occurred when the gear in contact was changed from No. 1 to No. 2 (Fig. 18), and this is estimated to be the origin of the difficulty in shifting. Figure 20-a shows specification F, an improved chamfered form designed to enable the pinion gear stroke to increase with increasing angle, even when the gears in contact change (Fig. 20-b). Specification F displayed excellent shift performance in vehicle tests.

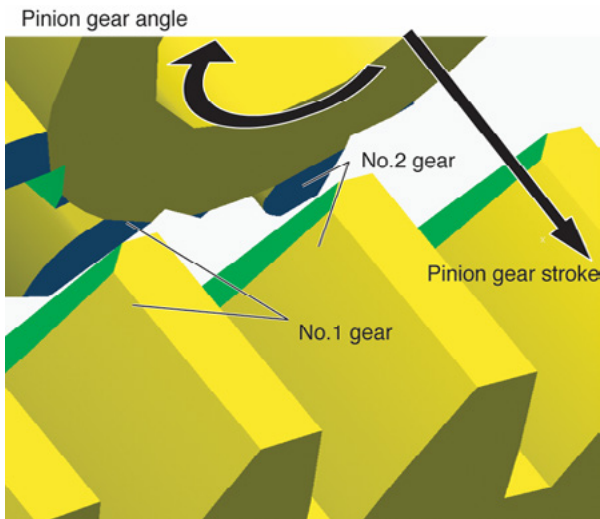


Fig. 18 Direction of pinion gear angle and stroke

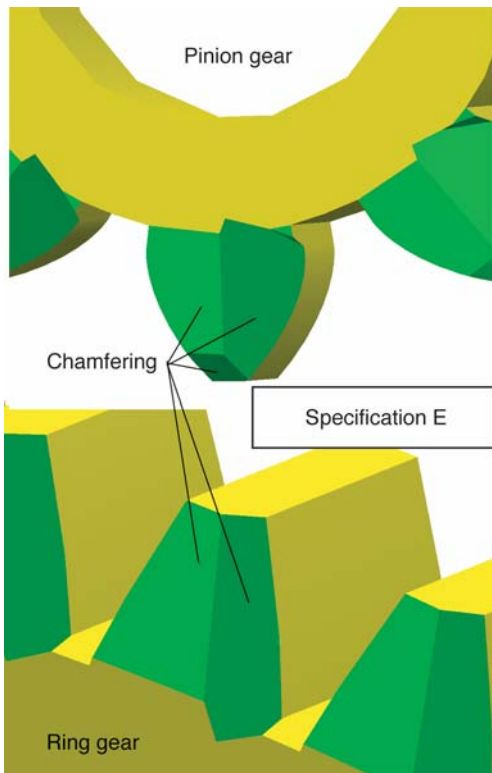


Fig. 19-a Chamfering form of gear end face

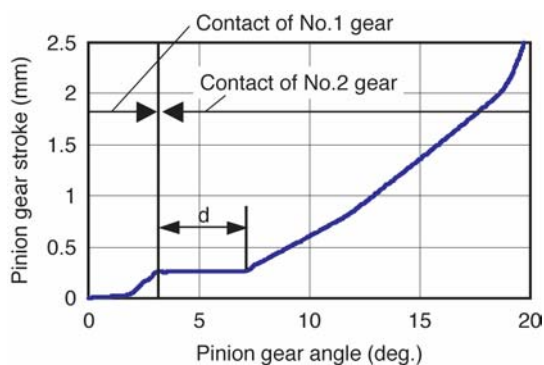


Fig. 19-b Relationship between pinion gear angle and stroke

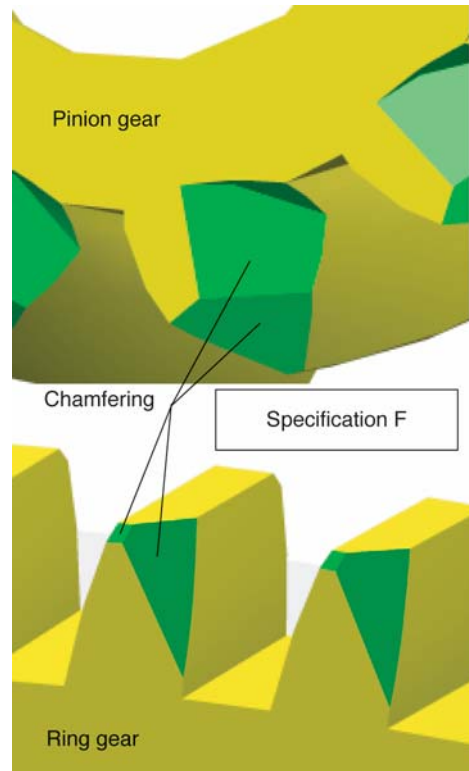


Fig. 20-a Chamfering form of gear end face

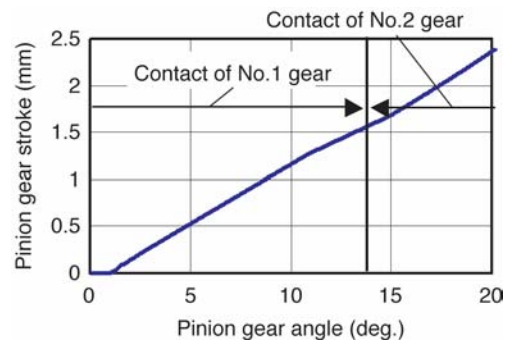


Fig. 20-b Relationship between pinion gear angle and stroke

6. Summary

Research conducted on noise reduction for pinion gear shift-type starters produced the following results:

- (1) Pinion shift noise and cranking noise are both elements of noise at engine start; cranking noise is produced for a longer period, and therefore generates a higher level of discomfort for occupants of the vehicle.
- (2) Cranking noise is composed of gear rattle and gear whine, but gear whine is dominant.
- (3) Measures to decrease cranking noise in spur gears have little effectiveness, and are therefore impractical.
- (4) Employing helical gears to increase contact ratio decreased cranking noise in the cabin by 7 dB.

The following methods were utilized to establish gear specifications:

- (1) Stress analyses were conducted for the sections making contact when the end faces of the pinion gears and ring gears strike. The rate of generation of stress exceeding the elastic limit was established as an indicator of potential damage to the end faces.
- (2) Excellent shift performance was achieved by establishing a setting at which pinion gear stroke increased with increasing angle during shift.

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