NEW TRACTION MACHINES WITH HELICAL GEAR FOR HIGH SPEED ELEVATORS

Yoshitaka Matsukura, Ph.D., Shinji Yamasaki,
Sumio Yoshioka, Ph.D., Michio Kumasawa
Mitsubishi Electric Corporation, Inazawa, Japan

ABSTRACT

To meet the demands such as energy saving and smaller power source equipment in buildings, Mitsubishi has developed high-speed elevators introducing a new system, which employs the helical gear type traction machine and the VVVF control, first in the world. This paper describes the basic design concept concerning fatigue stress, impact stress, pitting, wear and vibration of the helical gear that is an important part to the traction machine and introduces the outline of the results of the development.

1 BASIC DESIGN CONCEPT

Described below are the technical subjects of the helical gear for elevators classified by factors.
(1) Securement of strength against cyclic bending stress caused by variation in load and start and stop operations of the elevator
(2) Securement of strength against ultimate impact bending stress due to drastic variation in load when the safety device of the elevator operates or the car strikes the buffer
(3) Securement of strength against pitting and wear in tooth surface resulting from long-term operation
(4) Reduction of vibration and noise caused by engagement of gears in the car, the hall and the room
We will explain the basic design concept of the helical gear for elevators with regard to the above subjects classified by factors.

1.1 Strength against Cyclic Bending Stress

As a high-speed elevator is installed in a high-rise building of which traffic is busy, number of operations sometimes exceeds 240 times per hour. And, the total number of operations during its service life is over 20 million times. Torque works on the gear in both forward and reverse directions owing to loads. The gear must have sufficient strength to these loads and not break due to fatigue. To attain this purpose, it is necessary to grasp runout in both directions and ultimate bending fatigue stress of the gear, additionally, establish a design method of fatigue stress of the helical gear with the evaluation of cyclic load applied over 10^7 times and fatigue cracks taken into account.

1.2 Strength against Impact Bending Stress

An elevator is equipped with such safety apparatus as the braking device, the safety device and the buffer. These safety apparatus function to ensure safety of passengers when an unexpected accident occurs. If these safety apparatus operate, an impact load works on the gear. The gear must not suffer damage even if it bears an impact load. Also, it must withstand normal operation for a long time after an impact load acted.
Regarding this subject, it is required to seize characteristics of strength of high-hardness materials possessing stress concentration against impact. Also, using the actual elevator and actuating the safety apparatus, it is important to confirm impact resistance by conducting an impact stress test.

1.3 Strength against Pitting and Wear

An elevator performs over 20 million times of start and stop operations during its service life, and, the total traveling distance exceeds 300,000km. Under these conditions, damages such as pitting and abnormal wear in the gear and a decline in quality and performance of the elevator system due to the above damages must not occur. Heat treatment methods, hardness, materials, lubricant are regarded as the factors that give an influence on strength, so that it is necessary to grasp characteristics of pitting and wear resulting from these factors.

1.4 Vibration and Noise Caused by Engagement of Gears

An elevator is sometimes installed in a building in a relatively quiet environment such as an office, a hotel or a residence. Therefore, transmission of vibration and noise caused by engagement of gears to the inside of the car, a hall or a room must be restricted to the minimum. In order to satisfy this subject, there is a way of reducing vibration and noise in those propagation routes, however, it is fundamentally needed to decrease vibration and noise produced by engagement of gears.
For this purpose, establishment of a control level for specifications of gears, configurations of teeth and working accuracy is required besides investigation of factors of them. Furthermore, antiresonance design of the gear box and the shaft must be examined.
Explained above are the basic design concept and subjects of the required performance of the helical gear for elevators. We made a systematic inspection, covering from basic test to test using the actual elevator, for achieving these subjects. And, as a result, we have developed and put a high-performance low-noise helical gear to practical use.

2. BENDING STRENGTH OF GEAR

strength of gears against bending stress has been investigated in a wide range. But, there are a lot of factors such as materials, heat treatment methods and hardness, dimensions and working accuracy, residual stress, all of which have an effect on bending stress of the gear. And, correlation among these factors is complicated. Therefore, strength design suitable for the working methods and heat treatment conditions of the gear is requisite.
Using standard gears, we apprehended bending stress under different conditions of working and heat treatment in the development of the helical gear type traction machine. And, for making a comparison with the test results of the standard gears, fatigue test was carried out with the actual elevator. Based on these results, we grasped an influence of each factor on bending stress and made the most appropriate design of the gear.

2.1 Static Bending Test

There have been various test methods of bending stress of gears suggested. Among them, a method, in which the load point is the highest point of single tooth contact and a load is applied to two teeth simultaneously, was adopted. A spur gear was selected as the fundamental gear, and such factors as material hardness and working conditions were evaluated. The result proved the following basic facts: ultimate static bending stress can be dealt with Niemann's comparative stress; ultimate static bending stress of the case hardening gear is lower than that of the induction hardening gear because of occurrence of cracks; ultimate static bending stress varies according to the difference in the configuration and displacement coefficient of the cutting hob. Figure 1 shows the test apparatus. In Table 1, ultimate static bending stress of the induction hardening gear and the case hardening gear are shown by comparison.

SCM440 (induction hardening)		SCM415 (case hardening)	
Module	Comparative stress*	Case depth (mm)	Comparative stress*
1.5	239	0.4	230
		0.8	165
3.0	216	0.8 (impact)	174

Note * Niemann's comparative stress: (kg/mm^2)

TABLE 1 Ultimate static stress

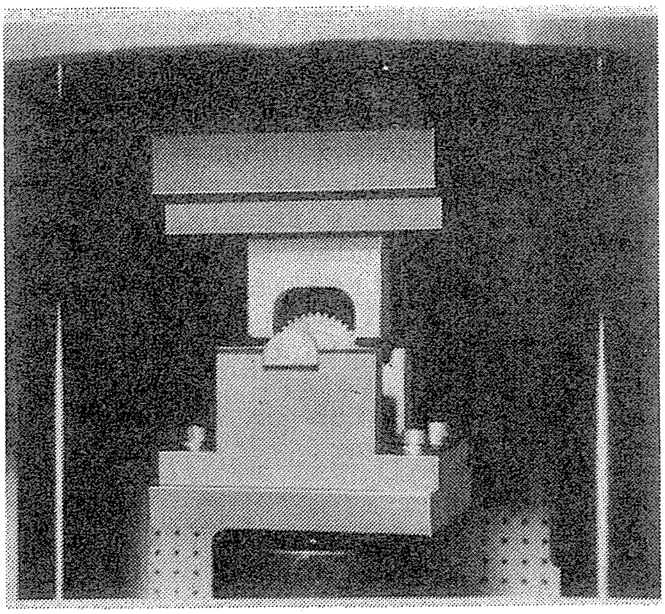


FIGURE 1 Bending test apparatus of gears

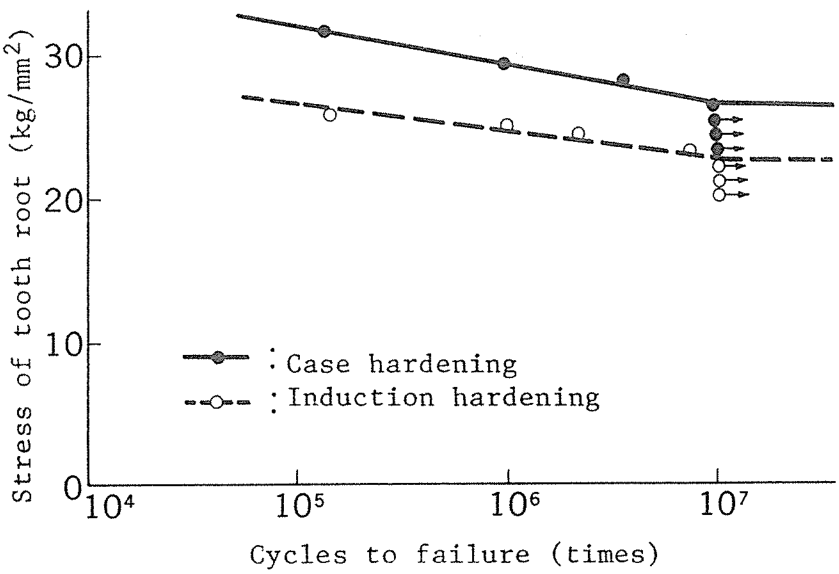


FIGURE 2 Results of fatigue test of gears

2.2 Bending Fatigue Test

(1) Bending fatigue test using standard gears

By adopting the same test method as static bending test shown in Figure 1, bending fatigue test was carried out with fundamental gears. Like the static bending test, an analysis of residual stress and non-propagating fatigue cracks in the bottom of teeth was made in addition to examination of each factor. The results made clear that fatigue stress can be increased according to the configuration of the cutting hob, influence of residual stress is large, and, fatigue stress is not proportional to ultimate static bending stress. In Figure 2, results of the fatigue tests of a standard case hardening gear and a standard induction hardening gear are given. Fatigue stress of the case hardening gear is larger than that of the induction hardening gear by about 20%.

(2) Fatigue test using traction machine
Engaging condition of gears is different due to working errors of tooth profile, tooth trace, pitch, etc. Load operating on the teeth also differs. In addition, evaluation of a gear only is not enough because of influence of contact ratio. For the reason above, evaluation using a power circulating type test device combined with a pair of gears is generally carried out. This method can consider influence of working errors of gears, however, evaluation of influence of assembling errors is difficult. With a helical gear type traction machine for elevators, we conducted a cyclic load test utilizing an electric-hydraulic fatigue tester, a fatigue test by performing continuous operation by connecting a loading device, and a fatigue test by repeating start and stop operations simulating an actual elevator. These tests revealed that fatigue stress of gears equipped on actual elevators can be estimated from the results of a fatigue test of the standard gears, contact ratio and surface contact. Sufficient performance to cyclic load applied 5×10^8 times was confirmed under the severe condition of an elevator. Demonstrated in Figure 3 is the electric-hydraulic fatigue test apparatus.

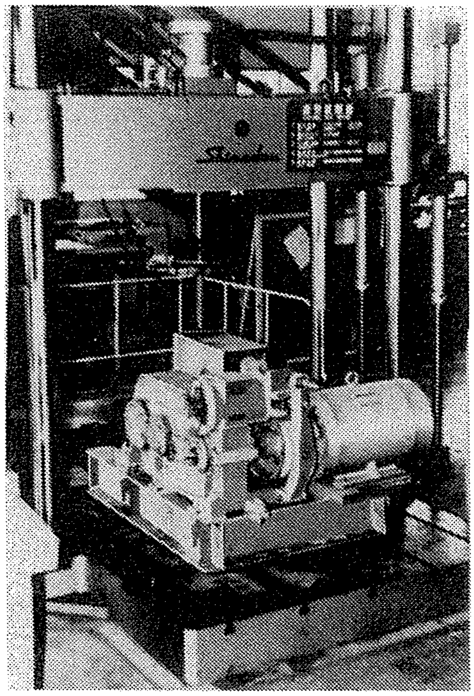


FIGURE 3 Fatigue test apparatus of traction machine

2.3 Impact Bending Test

(1) Design concept of ultimate impact bending stress
Miniaturization and higher performance of helical gears have been pursued by such methods for higher hardness as induction hardening and case hardening. In general, it is said that high-hardness materials have small total impact absorption energy and is inferior in strength against impact. But, this is a characteristic with rupture of the materials taken into consideration, and in designing

of apparatus, design is made within the range of elasticity. Also, in design of impact stress, the same notion may be necessary according to the conditions, and, maximum impact load (stress) should be regarded as one of design standards. Based on this notion, we investigated mechanism of impact rupture of high-hardness materials and seized impact bending characteristics of each material, then, confirmed performance on the actual elevator.

(2) Ultimate impact bending stress of high-hardness materials

For analyzing mechanism of impact rupture, measurement of impact load and amount of deformation is required. By using an impact tester provided with measuring devices for these values, we investigated behavior and characteristics of ultimate impact bending stress with regard to the factors including materials, hardness and stress concentration factor. Figure 4 shows data of impact bending test, and Figures 5 and 6 indicate impact bending characteristics. They made clear that: maximum impact load increases with heightening of hardness of the material; total impact absorption energy does not depend on hardness of the material in case stress concentration exists; ultimate impact bending stress increases proportionally to ultimate static bending stress; ultimate impact bending stress can be an index in design of impact of a high-hardness material. We also conducted a similar impact test utilizing test pieces of tooth shape. The results are given in Table 1. It was found that tooth-shape test pieces possess satisfying ultimate impact bending stress and ultimate static bending stress.

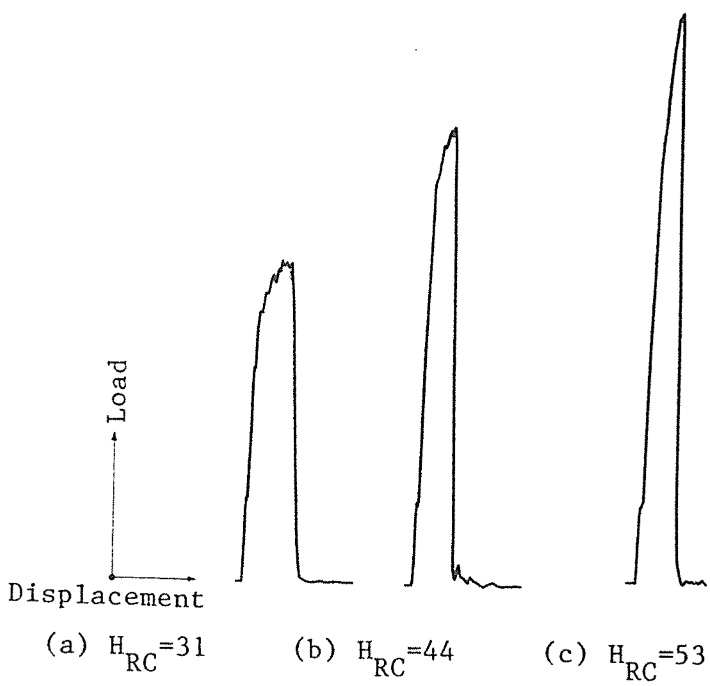


FIGURE 4 Relation between load and displacement in impact bending test

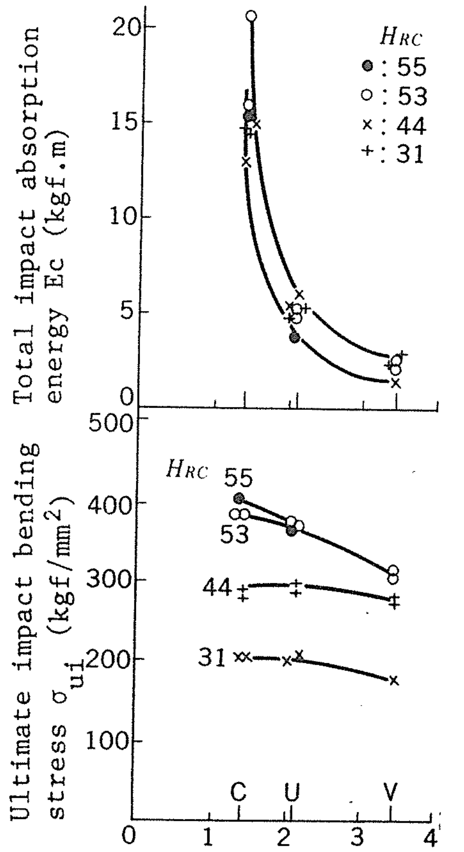


FIGURE 5 Instrumented charpy impact test results

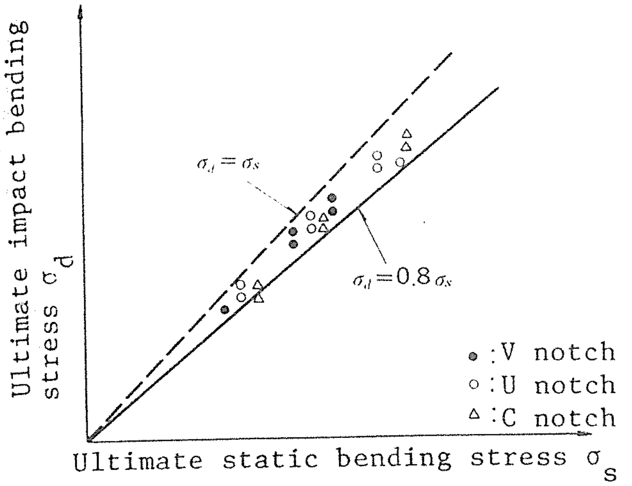


FIGURE 6 Relation between ultimate impact bending stress and ultimate static bending stress

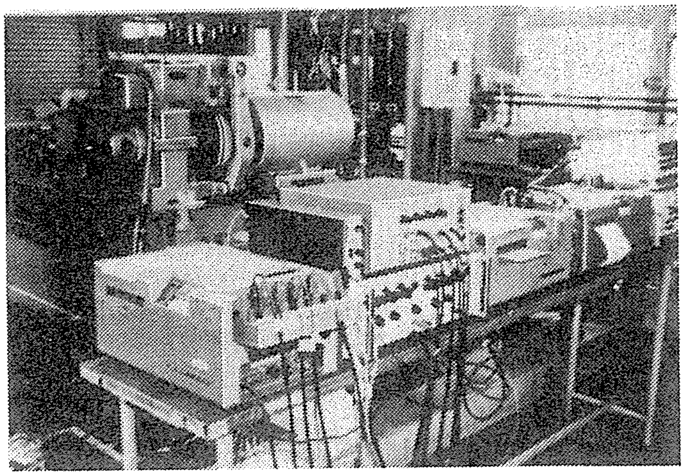


FIGURE 7 Impact test scene utilizing actual elevator

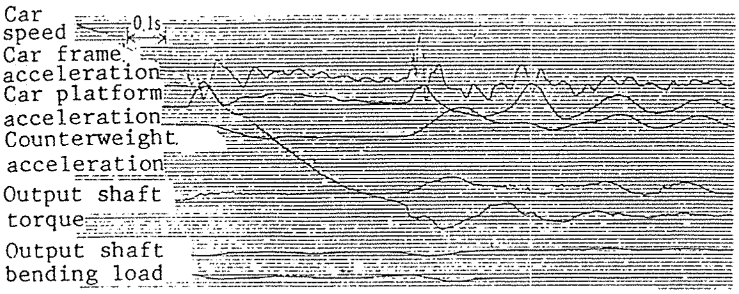


FIGURE 8 Data of impact test (Striking test to buffer)

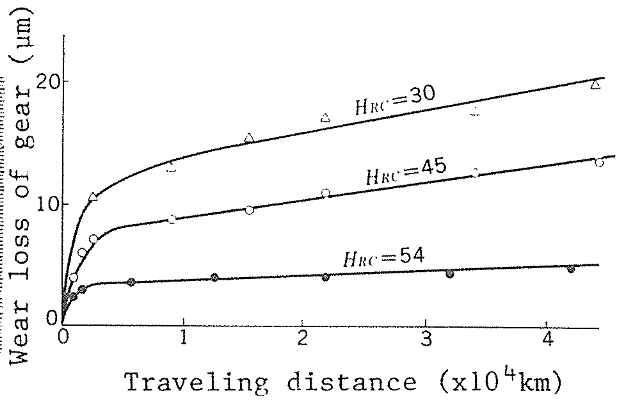


FIGURE 9 Wear characteristics of gears

On the other hand, an actuation test of the safety device and a buffer striking test were carried out by the use of the actual elevator on the assumption that an unforeseen situation occurred. These tests disclosed that the helical gear developed for this system offers satisfactory safety to these impacts. In Figure 7, the scene of the impact test is shown, and Figure 8 shows data when the car actually collided with the buffer. It made clear that working time of torque on the output shaft in striking becomes comparatively long and rise time of torque is slow. Besides, we carried out a damage analysis and a fatigue test of the helical gear after impact tests described above and found that the gear can endure a long-term use after bearing impact.

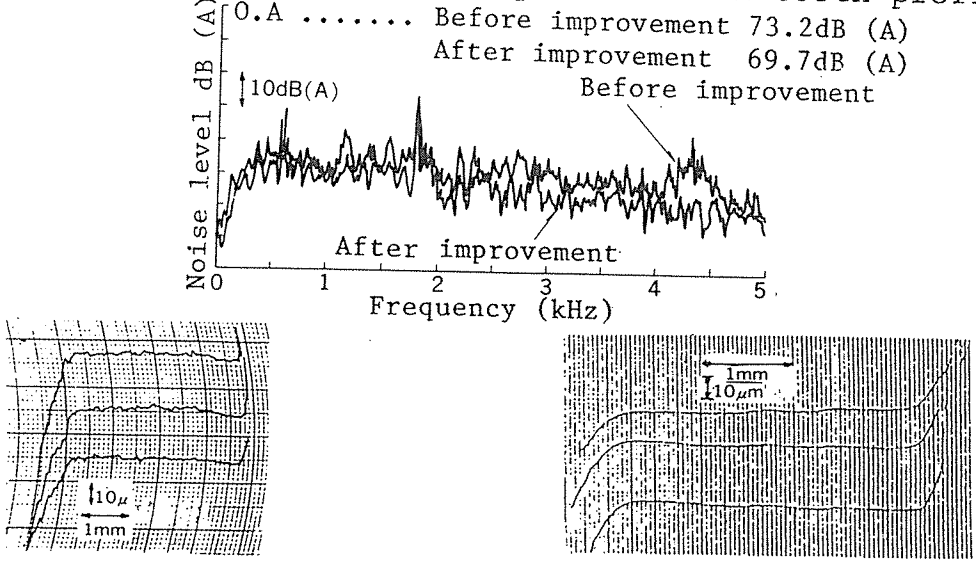
3 DURABILITY OF GEAR

For examining durability of a gear against pitting and wear, there is a method of conducting an equivalent test with a cylinder or a model gears. It is comparatively easy to carry out this test method, however, it holds some problems. For example, by this method, contact state due to working or assembling errors of gears and lubricating condition, which is supposed to have an effect on durability, cannot be simulated. We made basic evaluation of materials, hardness, surface pressure, speed, etc. by using model gears, and conducted an endurance test with an actual traction machine for total evaluation. Given in Figure 9 are wear characteristics of the gears in the test utilizing the actual traction machine. If gear hardness is $H_{RC}30$ or over, the gear comes in the stationary wear range when traveling distance is 2,000 ∿ 10,000km. With the total traveling distance of the elevator taken into account, we obtained a fact that hardness of tooth surface must be around $H_{RC}50$. Further, in the endurance test using the actual traction machine under severe conditions simulating an elevator, there was no problem concerning durability against pitting and wear.

4 VIBRATION AND NOISE OF GEARS

Miniaturization and lightness of a traction machine for elevators can achieve not only reduction of load working on buildings but also installation of a traction machine in a narrow machine room. Accordingly, miniaturization of the motor with high-speed rotation is necessary as well as miniaturization of gears. High-speed rotation of the motor, however, increases vibration and noise of the traction machine, so that low vibration and low noise are now important subjects.

Regarding vibration and noise of gears, a large number of documents and records have already been presented and proved that many factors such as working errors, profile modification, crowning, contact ratio and rigidity of teeth exert an influence on vibration and noise. We carried out a test and an analysis of effect of the aforesaid factors by the use of an actual traction machine to examine contribution ratio of each of them. Figure 10 shows variation in noise on account of improvement in tooth profile.



(a) Unimproved tooth profile

(b) Improved tooth profile

FIGURE 10 Noise after improvement in tooth profile

Improvement in amount of profile modification and surface roughness of teeth achieved reduction of noise in the entire frequency, concretely, by 3.5dB (A) in overall value. These results have provided us with a basic fact that errors of tooth profile and engagement have a great influence on vibration and noise, and, it is necessary to regulate the amount of profile modification to promote low noise. As for the gear box and the gear shaft, investigation was made by experiment and analysis, and antiresonance designing was also conducted. In Figure 11, an example of sound intensity analysis of a gear box is given. By this analysis, it was made clear that the bearing part of the intermediate gear and the bottom of the gear box resonate in the frequency about 3 times the engagement frequency of the input shaft.

Taking these factors related to design into consideration, we manufacture helical gear type traction machines for elevators under the strict quality control including working, in-process inspection and delivery inspection. As a result, noise has been reduced to 69 ∿ 73dB (A) and we have obtained an extremely silent helical gear type speed reducer. Figures 12 and 13 show the scene of in-process inspection and the scene of the delivery inspection of the traction machine respectively.

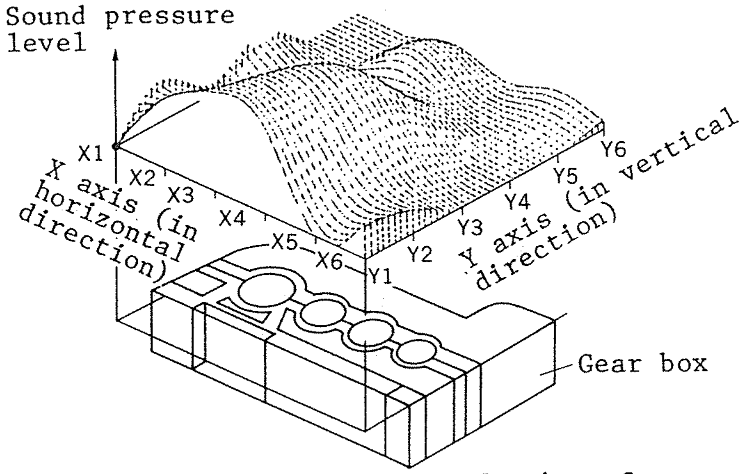


FIGURE 11 Sound intensity analysis of gear box

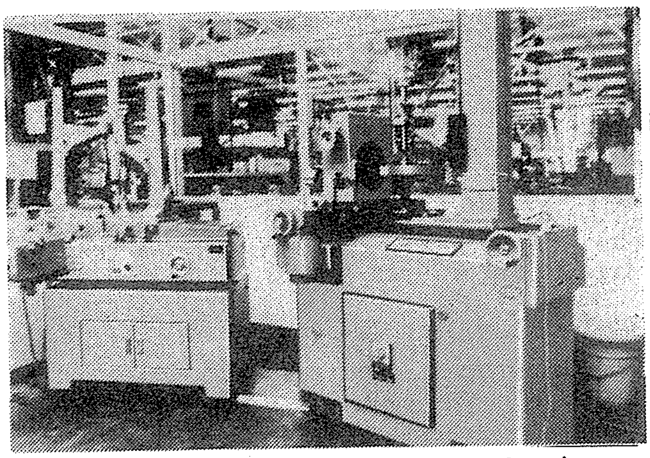


FIGURE 12 Inspection device of gears

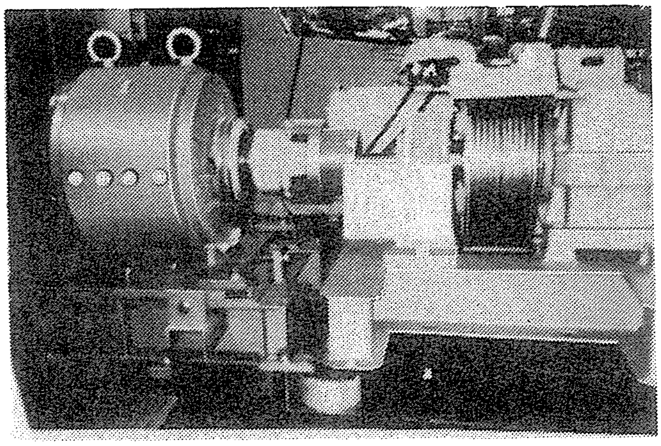


FIGURE 13 Delivery inspection of traction machine

5 CONCLUSION

We introduced technical subjects and the results of development of the helical gear for elevators, which had recently been developed and put to practical use. This traction machine is manufactured by high-accuracy working technology and antiresonance design technology and under the strict quality control. To say nothing of high performance, safety and reliability are given full consideration, and we firmly believe that the elevators can meet requirements of users. We continue to strive for comfortable riding and high performance and make each and every effort to expand the range of its applications.

REFERENCES

Watanabe,E., Yokota,S., Kamaike,H. and Yamasaki,S.(1983). "The VVVF control system for high-speed elevators", Mitsubishi Denki Giho, Vol 57, No. 11, 1983, pp 739-743

Kumasawa,M., Yoshida,S., Demizu,M. and Yamasaki,S. (1985). "Impact strength for notched high strength steel", Journal of the Society of Materials Science, Japan, Vol 34, No. 381, June 1985, pp627-632

Yamasaki,S., Yoshioka,S. and Kumasawa,M.(1983). "The investigation of impact strength of helical gears for elevators", Monographs in Lecture of Journal of the Japan Society of Mechanical Engineers, No. 830-15, 1983, pp 5-8

Fujita,K., Yoshida,A. and Nakase,K.(1979). "Effect of difference in hardness on surface durability of 0.45 percent carbon steel rollers", Journal of Japan Society of Lubrication Engineers, Vol 24, No.6, 1979, pp 377-383

The Japan Society of Mechanical Engineers, (1980). RC-SC48 Reports of Study Results by Section Meeting on Inspection and Study of Prevention of Vibration and Noise of Gears, 1980