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REDUCTION GEAR FOR HIGH SPEED GEARED TURBINES

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I. INTRODUCTION

Reduction gears are widely used in coupling high speed steam and gas turbines with low speed generators, motors with high speed compressors and turbo-machines of different shaft speeds.

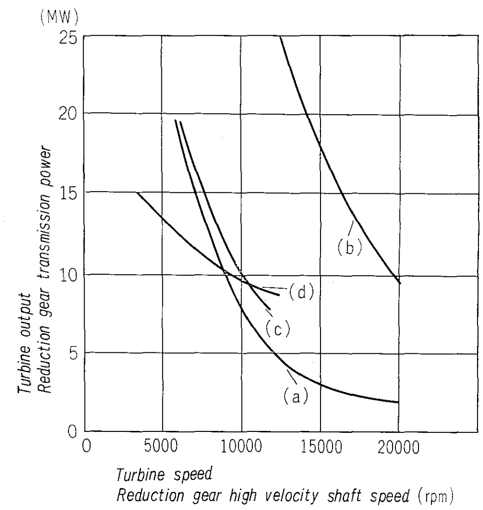
The trends recently in steam turbine plants for domestic power have been to improve the heat economy by raising the pressure and temperature at the steam inlet, increase efficiency by the use of a geared turbine and design the equipment to be more compact. Reduction gears used in geared turbines generally must have a high transmission power and high speed. When used for electric power generation, they also require high reliability to withstand continuous operation under heavy loads and severe generator short circuits and also must be easy to maintain. The trends to high speeds and high power in steam turbines have been remarkable. Investigations by Fuji Electric have revealed the advantages in terms of both operating and production costs of increasing speeds in turbines with powers of up to approximately 20,000 kW. Applying the high speed large capacity turbines (speed : 8,000 to 20,000 rpm, output : 10,000 to 56,000 kW) developed for the compressor to electric power generation, the high speed large capacity reduction gears are required falling outside of all existing concepts.

This article will introduce the design concepts and practical results of the one-stage double axis reduction gears manufactured by Fuji Electric and also discuss future views concerning further increases in speed and power.

II. REDUCTION GEAR FOR STEAM TURBINE

Reduction gears for geared turbine generally contain one-stage double-axis gears or coaxial planetary gears. The former includes single helical and double helical types and the latter includes a type with the planetary axes fixed and another in which the outer ring with internal teeth is fixed.

Fig. 1 shows the relationship between maximum transmission power and high velocity shaft speed of various types of reduction gears (low velocity shaft speed : 3,000 rpm) and the maximum output and speed of steam turbines. If special considerations are made, they can be used over a rather wide range as seen in this limit diagram. In the diagram, (a) refers to Fuji Electric's standard industrial turbine and (b) is Fuji's high speed, high power turbine for compressor drive. These limit outputs are for a single casing and if coupled in tandem, still higher outputs are possible. (c) indicates the limit transmission power of the double-helical, double-axis type tempered reduction gear (for reasons explained later, all reduction gears for Fuji Electric's steam turbines are of this type) and (d) is the limit transmission power of the single helical reduction gear with one stage and double axes (surface hardened). There are few large capacity planetary gears and the trend is toward use of low capacity gears with large gear ratios. This is because, their construction is complex and maintenance is difficult when compared with double-axis reduction gears. It is also necessary to consider lubrication and vibration in relation to high level design and manufacturing techniques. The conditions required for reduction gears for geared turbines are



(a) Previous type steam turbine
(b) Industrial turbine with high power and speed
(c) Fuji Electric's standard reduction gear (Double helical)
(d) Single helical reduction gear with one-stage and double-axes

Fig. 1 **Limit diagram of single casing turbine output and reduction gear transmission power** as follows:

1) They must have high reliability in respect to continuous operation under large loads (they must be designed with a high degree of flexibility).
2) They must be resistant to shock loading during generator shorts and rapid load changes.
3) Construction must be simple and maintenance easy.
4) Operation must be quiet with no vibration noises in case of both loads and no loads.
5) The design must provide good contact characteristics in accordance with high speeds.
6) Loss must be small.
7) They must be stable and not use extensive tooth profile shifting which requires a high level of skilled work.
8) They must be produced by methods which require little precision processing and in which profile form and longitudinal form errors are slight.
9) The quality of the gear materials must be stable. Heat treatment must be performed carefully especially when cementation quenching and nitriding gears are used.
10) Gear ratios must be accurate and the center distance of the gear must be constant.
11) Flat bearings and thrust bearings must be designed reasonably. It is highly advisable that the design be such that no thrusts will occur especially when high powers are used.
12) There must be no problem in supplying lubricating and cooling oil to the gear surface.
13) The delivery time must be short and the price low.
14) The unit must be compact.

III. FEATURES OF THE FUJI REDUCTION GEAR FOR STEAM TURBINES

Table 1 shows the supply list of Fuji reduction gears for geared turbine including those already delivered and those under production. The total is 32 units with an overall transmission power of about 190,000 kW. All customers both in Japan and abroad have praised the high reliability of these gears. Since all the gears have been designed especially to be used with high speed and high power steam turbines which are becoming more common, considerations have also been given to even greater

Table 1 **Supply list of the reduction gear for high speed steam turbine**

Customer	Transmission power (kW)	Speed (rpm)	Delivery date	Model No.
Nippon Light Metal (Shimizu)	5,840	6,000/3,600	1957	Tb45
Furukawa Mining (Yoshima)	4,170	7,000/3,000	1958	Tb45
Yokohama Suger Refining (Okayama)	1,640	7,200/1,800	1959	Tb45
Idemitsu Kosan (Tokuyama)	3,610	5,000/3,600	1960	Tb40
Idemitsu Kosan (Chiba)	3,380	5,000/3,000	1960	Tb40
Nippon Kokan (Mizue)	7,010	6,000/3,000	1960	Tb50a
Nippon Kokan (Mizue)	7,010	6,000/3,000	1960	Tb50a
Fuji Seito (Misawa)	2,320	8,000/3,000	1961	Tb36
Daishowa Paper (Yoshie)	6,280	5,000/3,000	1962	Tb45
Kyushu Oil (Oita)	2,670	8,000/1,800	1963	Tb45
Idemitsu Petrochemicals (Tokuyama)	5,990	6,000/3,600	1963	Tb45
Sanko Paper (Sobue)	10,120	6,000/3,600	1963	Tb50a
Japan Zeon (Takaoka)	7,530	8,000/3,600	1963	Tb45as
Nippon Kokan (Tsurumi)	960	6,000/3,000	1964	Tb26
Asahi Chemical (Nobeoka)	1,660	10,750/4,050	1964	Tb26
Asahi Electrochemical (Ogu)	9,510	6,000/3,000	1964	Tb50a
Japan Zeon (Tokuyama)	7,340	6,000/3,600	1964	Tb45
Chisso Cor. (Minamata)	8,280	8,000/3,000	1964	Tb55
Oriental Chemicals (Korea)	5,660	8,000/3,600	1967	Tb45
Nippon Light Metal (Shimizu)	7,310	7,000/3,600	1967	Tb50
Toa Oil (Kawasaki)	3,130	8,000/1,500	1968	T62
Japan Zeon (Tokuyama)	11,980	6,000/3,600	1968	Tb50a
Jujo Paper (Miyakojima)	7,300	6,000/3,600	1969	Tb45
Korea Power (Cheju Island)	5,210	6,500/3,600	1969	Tb45
Korea Power (Cheju Island)	5,210	6,500/3,600	1969	Tb45
Fuji Oil (Izumisano)	5,320	8,000/3,600	1969	Tb45
Chisso Cor. (Goi)	9,580	8,000/3,000	1970	Tb55
Yokohama Sugar Refining (Okayama)	1,620	10,000/1,800	1970	T45
Sanko Paper (Sobue)	10,420	6,500/3,600	1970	Tb50
Samitt (Thailand)	6,250	8,000/3,000	1970	Tb45
Samitt (Thailand)	6,250	8,000/3,000	1970	Tb45
Japan Oil (Mizushima)	4,170	8,000/1,800	1970	T57

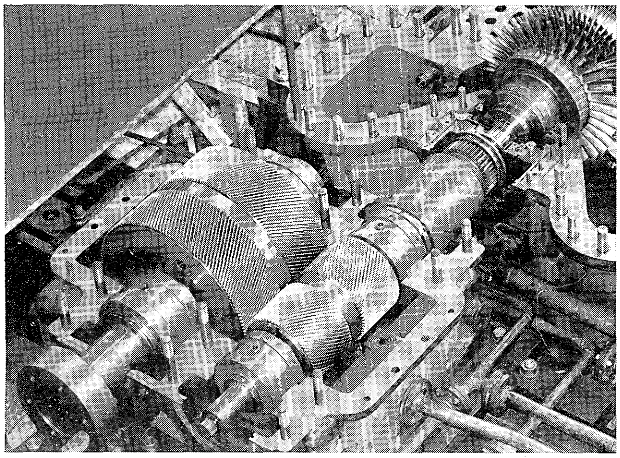


Fig. 2 Reduction gear being assembled

increases in the future.

Fig. 2 shows a reduction gear being assembled for test operation of a 7,000 kW bleeder condensing turbine.

The features of this reduction gear for geared turbine are as follows:

1) Double-helical one-stage double-axis gears
2) Quenched and tempered gears (CrMo and NiCrMo steels)
3) Small module
4) Special profile shifting
5) Cast iron gear box
6) Standard series and short delivery period
7) High manufacturing accuracy
8) All design calculations have been made by a FACOM 230–50 computer

A more detailed explanation of some of these features follows.

1) Double-helical one-stage double axis gears

This gear construction is extremely simple and checking and maintenance are very easy. Inconveniences concerned with handling of double-axis shift can be compensated for.

In the double helical system, the thrust bearings to balance the large thrust produced in single helical gears are unnecessary and thus there is no bearing metal fault. In high speed gears, it is necessary to increase the number of contacting gears in order to keep the transmission of power smooth and the helical angle should also be large. In double helical gears, there are no limitations in practice concerning such requirements but in the single helical gears, it is necessary to have a small helical angle because of the previously described thrust due to power transmission.

Shocks are produced in the forward and reverse directions when short circuits of the generator occur, but double helical gears are especially favorable in this respect. In gears with a high ratio, the diameter of the pinion is small and this causes a divergence in the axis direction of the gear surface stress due to axis deflection and twisting. However, in double helical gears, the thrust in the rotation direction is automatically balanded and the transmission power in the two helical surfaces becomes equal. Therefore, the gear width in respect to the same axis deflection can be about two times that in the single helical gear and it is possible to reduce the reduction gear weight considerably. In addition, the peripheral speed at the tooth contact point in respect to the same transmission power can be minimized, the dynamic load decreased and the noise level reduced. In the double helical gear, lubricating oil can be added in the central part of the gear surface and even if the gear width is large, the oil supply can be uniform which is especially advantageous in the case of high speed gears.

2) Quenched and Tempered Gears

The gear is made of CrMo steel and the pinion is made of NiCrMo steel. Materials in gears for geared turbine should be quenched and tempered for the following reasons.

The tooth stress consists of bending stress of the tooth root and the surface stress. Generally in gears which are surface hardened, the permissible transmission power is determined by the bending stress of the gear tooth root, and when the gear is quenched and tempered, it is determined by the surface stress.

In the former type of gears, the module is large in order to make the root stress low, i.e. it is designed so that the number of gears are small. In gears designed and manufactured in this way, uniformity of the surface treatment layers becomes extremely important. In particular there is a chance of major faults occurring due to tooth loss when shock loads are applied. In Fuji Electric gears however, flexible type design is used. Another great advantage in the use of quenched and tempered materials is that one cutter can be used for both rough cutting and finishing and it is only necessary to fix the material in the machine once. The processing is carried out in a thermostatic chamber using suitable cutting conditions determined for each case. In other words, in the additional processing due to surface hardening there is not only a time loss but also a danger of a drop in the processing accuracy with the extreme conditions in high speed gears.

3) Small module

Since the transmission power per unit gear width is small and there can be a margin in the design, it is possible to make the module small in accordance with the tooth root stress and transmission power quiet because of the large number of teeth contacts. The gear ratio accuracy improved.

The gear surface sliding speed inevitably becomes small and this makes possible highly efficient operation due to the small wear loss.

4) Special profile shifting

The amount of profile shift is determined on the assumption the product of the sliding speed and the gear surface pressure has considerable influence on the occurrance of gear surface pitching. This also makes possible the minimum wear loss and quiet operation with few shocks in the teeth contacts. At Fuji Electric, an amount of profile shift calculated on the basis of a theorectical analysis is applied in the design of all gears and it is no exaggeration to say that the use of this special profile shifting increases the excellent characteristics of Fuji reduction gears for geared turbine.

5) Cast iron gear box

The gear box is made of cast iron with a high damping capacity and the large reduction gears have a double casing construction. Sufficient consideration has been given to noise.

6) Standard series and short production period

For these reduction gears:

gear ratios 1 to 4.2: 19 series
gear ratios 4.3 to 10: 21 series
transmission power: 100 to 20,000 kW
max. pinion speed: 14,000 rpm

It is possibe to start fullfilling orders using existing equipment and the delivery period is thus shortened. All of the above series are based on the aforementioned design concepts, and the highly flexible standard series have proven very successful.

7) High processing accuracy

Processing is highly accurate due to the use of Maag gear cutting machines and the level is JIS 0 clss. There is also no longitudinal crowning which requires a very high level of processing techniques. Therefore, there is no need for breaking-in operation. *Fig. 3* shows a large gear being cut.

8) Completely computerized design calculations using FACOM 230–50

The use of a gear design program developed by Fuji Electric made possible optimum design by facilitating such complex calculations as profile shifting, and the influence of axial torsion, bending and oil films on gear surface strength. All of the numerical values of parts which change in the individual products in accordance with the design specifications of transmission power, turning speed and gear ratio among the design drawing dimensions of the standardized series, including number of extra teeth and base tangent length, are given as output.

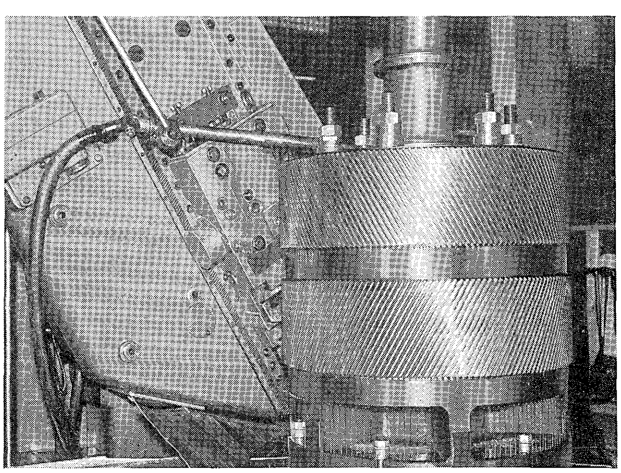


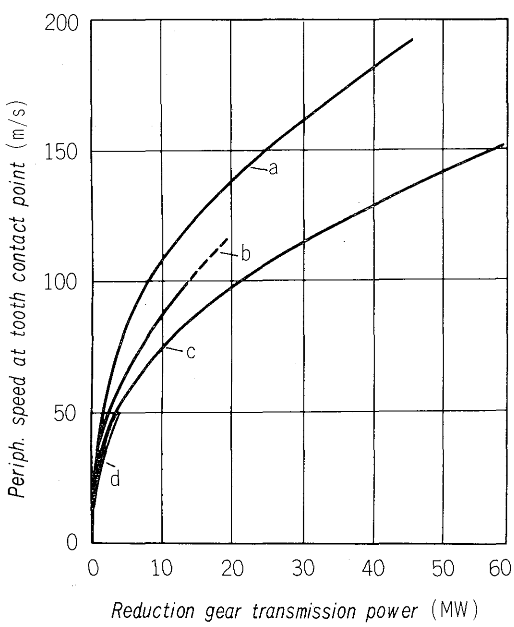
Fig. 3 Wheel gear being cut

IV. HIGH SPEED, HIGH POWER REDUCTION GEARS

When classifying reduction gears with high velocity axis speeds of over 3,000 rpm and transmission powers of 5,000 kW or less as small capacity, between 5,000 and 10,000 kW as medium capacity and over 10,000 kW as large capacity, because the transmission power in low capacity machine is small, the thrust is small and the module can be made small. Therefore, single helical gears are sufficient. For medium and large powers gears as shown in *Fig. 1*, double helical gears are better than the single helical types. The geared turbine output of previous models is compensated for the transmission power of the Fuji standard reduction gears and presents no problem. However, there has recently been an international trend toward higher power and it is necessary to consider high speed high power reduction gears with a view to the future.

Recently, a high speed high power steam turbine *Fig. 1* (*b*) which exceeds all previous ranges was developed as a prime mover for driving a high speed high capacity compressor in a well-known petrochemical plant. Since a reduction gear was utilized to the turbine for power generation, it opened a new period of development for the reduction gear. There are several problem points concerning high speed, high power geared turbines. One is economic, i.e. the balance of the cost reduction due to the higher speed of the turbine and the cost increase due to the addition of the reduction gear for example. Another is the technical problem of designing and manufacturing the gears. The cost are influenced by the numbers produced and only the technical points will be explained here. *Fig. 4* shows the peripheral speed at teeth contact and the transmission powers of various types of reduction gear according to Dr. Ehrlenspiel. In high speed high power equipment, vibration loading, noise, increased loss and gear surface lubrication can become problems. In the double-axis type gears, the increased plane bearing load due to the reaction force which always occurs due to the transmission torque also presents a problem.

The results of detailed investigations of experience in processing accuracy when manufacturing and designing reduction gears with a high velocity axis speed of 20,000 kW have shown that a special double axis type double helical quenched and tempered gear is best and gear cutting on the basis of a high level of quality control is possible as a precondition. The design specifications are shown in *Table 3*, a schematic arrangement is given in *Fig. 5* and the outer dimensions are shown in *Fig. 6*. The most important



(a) One-stage double-axes type
(b) Planetary gear (planetary axes fixed)
(c) BHS multi-purpose gear
(d) Planetary gear (Outer ring with internal teeth fixed)

Fig. 4 Peripheral speed at tooth contact point of various types of reduction gear

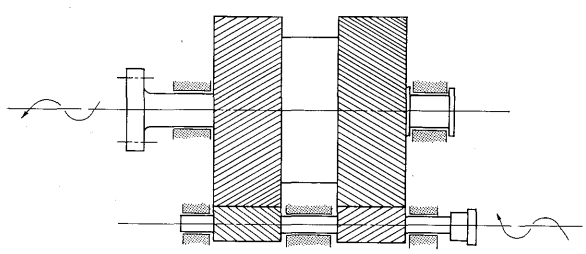


Fig. 5 Schematic arrangement of the high speed, high power reduction gear

Table 2 **Design data for high speed, high power reduction gears**

Type	Double helical gear of quenched and tempered steel with special double axes
Max. transmit. power	20,000 kW
Speed (Pinion)	15,068 rpm
(Gear)	3,000 rpm
No. of teeth (P)	44
(G)	221
Module	4
Pressure angle	20°
Helix angle	30°
Material (P)	NiCrMo-Steel
(G)	CrMo-steel
Tooth surface hardness (P)	H_B 248 or over
(G)	H_B 207 or over
Center distance	620 mm
Lloyd's K value	240 lb/in²
Peripheral speed at pitch circle	165 m/s
Tooth bending stress	2.9 kg/mm²

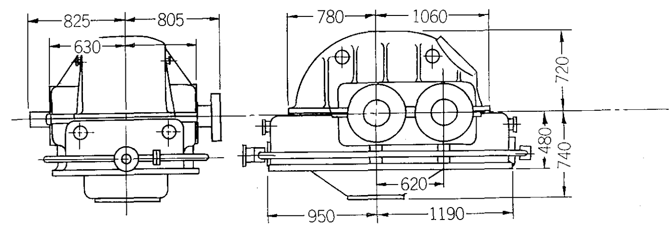


Fig. 6 Outer dimensions of the high speed, high power reduction gear

points concerning design and manufacture are as follows:

1) In order to prevent uneven load distribution due to bending in the pinion axis, a triple bearing construction is used for the bearing part at the center of the gear width.
2) Quenched and tempered materials are used so that the gear processing accuracy is increased and vibration loads are minimized.
3) Safety is high since the transmission power per unit gear width is small and the tooth root stress has been held to a minimum.
4) Special attention has been paid to providing suitable rigidity in the bearings and providing excellent bearing characteristics when small loads used.

V. CONCLUSION

This article has described reduction gears for geared turbines from the viewpoints of both a reduction gear maker and an industrial turbine maker. It has included an outline of the development of high speed high power reduction gears progressing on the basis of Fuji Electric's large amount of design and manufacturing techniques, and also shown the prospects for practical application of such equipment.

It is very improtant that existing notions concerning reduction gears be done away with in order to keep up with the technological revolution now in progress. The author wishes to thank all users for their cooperation and guidance which is hoped will continue.

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