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TRACTION DRIVE CVT TECHNOLOGIES FOR AIRCRAFT EQUIPMENT

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ABSTRACT

In 1996, research activities on traction drive CVT technologies was commenced in order to apply them to aircraft equipment. Extensive efforts have been conducted to overcome various technical barriers such as weight and severe environmental conditions with employing high speed traction drive technology, a split power mechanism and a sensorless control method using "Observer". Using these technologies, a all new concept IDG called "T-IDG®" has been developed.

Keywords: Traction Drive, CVT, Helicopter, IDG

INTRODUCTION

When a traction drive continuously variable transmission (T-CVT) is applied to a machine , it improves the machine's performance, fuel efficiency, etc. Because the T-CVT can generate an ideal output performance (such as torque, revolutional speed and power) in any conditions while the prime mover (engine) operates at the most efficient point. This fact has been proved in automobiles[1][2]. If the T-CVT is applied to aircraft equipment, it can be expected to obtain similar advantages. But to realize this, there are various technical barriers to overcome in weight, severe environmental conditions,etc. In this paper, the merits to apply the T-CVT to aircraft equipment, technical innovations to overcome the barriers and an overview of development tests are presented.

PLINCIPLE OF T-CVT[3]

Traction drive is a method to transmit power by shear resistance of specific oil called traction fluid, which has very high pressure-viscosity coefficient. When this is applied to a CVT, a configuration like Figure 1 is preferred. This is called "half toroidal type traction drive". A pair of Mt. Fuji shaped discs are facing each other and between them a pair of roller elements (power rollers) are clamped. By tilting the power rollers as shown in Figure 1, the speed ratio between the input and output can be changed continuously.

How to tilt the power roller is illustrated in Figure 2. The roller is tilted by the force "Fs", which causes the rotating moment around the tilting axis. The tilting force "Fs" is generated by the lateral shear force of traction fluid which is caused by shifting the roller a little (around several μm to 50μm) from the center of the disc using the hydraulic servo-piston. Once a desired speed ratio is obtained the roller position is set back to the center of disc, then the tilting action ceases because the tilting force "Fs" disappears at this point.

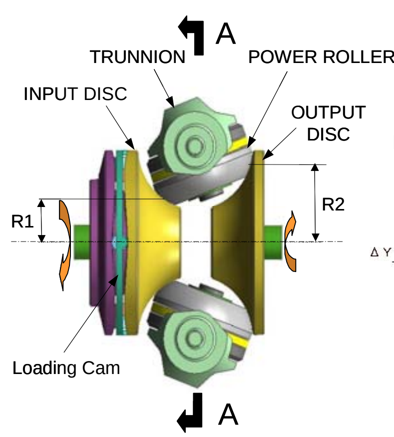

Figure 1 -
Principle of Traction Drive

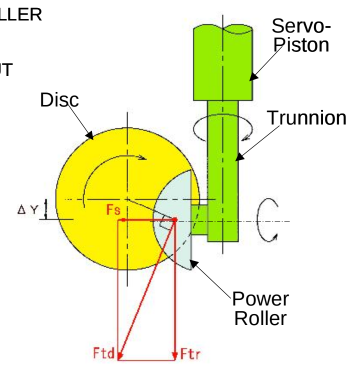

Figure 2
Tilting Action
(Sect. A-A of Fig.1)

ADVANTAGES FOR AIRCRAFT EQUIPMENT

When the T-CVT is applied to aircraft equipment, various advantages can be obtained. Some examples are described here.

Variable Rotor Speed Transmission for Helicopters

Helicopters, having a variable rotor speed transmission, can reduce the rotor speed and suppress the noise in noise sensitive areas such as urban environments. In less sensitive areas, such as countryside, the rotor speed can be set back to the most effective speed.

To realize this concept, adopting a toroidal traction drive CVT is the best selection because it has the largest torque capacity compared to other CVT methods, no torque break during speed change and high speed capability. Figure 3 shows the concept design of the variable rotor speed transmission for a 4.5 ton class twin engine helicopter[4]. The T-CVT is located at the high speed input section to reduce torque and reduce weight. The input speed is 23,000 rpm and the rating power is 800hp continuous. The helicopter can vary the rotor speed from 280rpm to 350rpm (20% variable range).

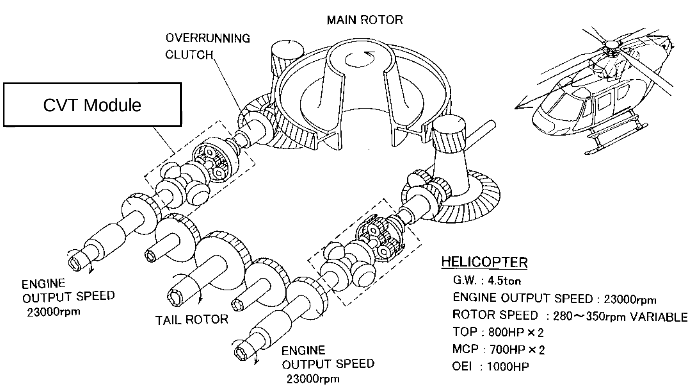

Figure 3 - Variable Rotor Speed Transmission

Constant Frequency Power Generation Device

Most of aircraft install engine driven electrical power generators. They normally equip CVTs to generate constant frequency AC power regardless of engine speed. The Integrated Drive Generator (IDG) is such a power generating device which contains a CVT and a generator in a common housing. The location where the IDG is installed is shown in Figure 4.

The conventional IDGs use hydraulic pump-motor (hydro-static) type CVT that has a lot of friction and sliding parts and it also converts the rotating power into hydraulic power then re-converts it into rotating power, which leads to considerable power loss and parts deteriorations.

With replacing this hydro-static CVT with a traction drive CVT, these demerits can be reduced and various merits such as high efficiency (this leads to low fuel consumption, weight reduction) and high reliability can be obtained.

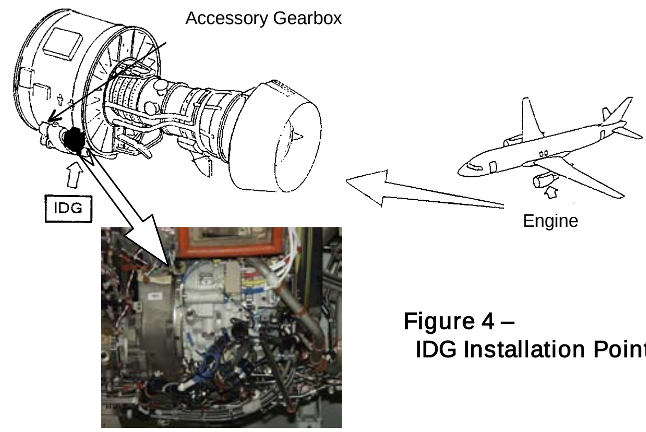

Figure 4 –
IDG Installation Point

TECHNICAL BARRIERS

There were various technical barriers in the following categories in order to apply T-CVT to aircraft equipment.

1) Light weight
2) High efficiency/High reliability
3) Environmental conditions
4) High response

Technical developments described in the coming sections have been conducted to break these barriers.

TECHNICAL DEVELOPMENTS

Light Weight

The size of the T-CVT can be reduced by reducing the transmitting torque. For a given transmitting power, torque can be reduced by increasing the rotational speed. Thus efforts were concentrated on making the rotational speed of the T-CVT as high as possible up to 23,000rpm which is three times as fast as automobile applications.

One achievement was the ceramic thrust bearing to support the power roller(Figure 5). Another one is low spin geometry of traction drive elements(Figure 6). In addition, the stability at high speed were carefully analyzed and the hydraulic control system were adequately tuned to eliminate instability[5].

Figure 5 –
Ceramic Power
Roller Bearing

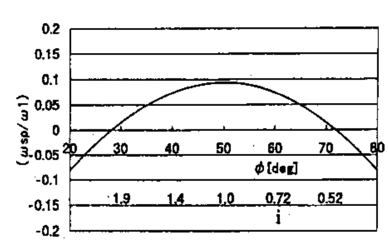

Figure 6 –
Low Spin Ratio

High Efficiency/High Reliability

The mechanical efficiency of toroidal traction drive is around 90% whereas that of gears are close to 100%. So a power split system in which the gear and traction drive share the power was developed to increase the overall efficiency . The concept of the power split system is illustrated in Fig.7. This is the CVT module of the variable rotor speed transmission shown in Figure 3. The input power is divided into two ways. One flows into the traction drive variator and another goes trough the bypass gear. Then these two are combined at the differential planetary gear. The output speed is variable from 4,800 rpm to 6,000 rpm whereas the input speed is constant at 23,000rpm. The system gear ratio was chosen so as not to cause torque re-circulation. Power flow into the two traction drive is shown in Figure 8. The maximum power flow into traction drive is limited to 277hp. With this design, it got to possible to realize a high power CVT which has the equivalent efficiency as a pure gearbox.[4][7]

In the conventional traction drive control circuit, a position sensor(e.g. LVDT)for the power roller is required to feedback its position. In stead of this, a sensor-less control was developed by adopting “Observer” control method, which can eliminate the LVDT and improves the system reliability. The control loop for the sensor-less control is shown in Fig.9 [6].

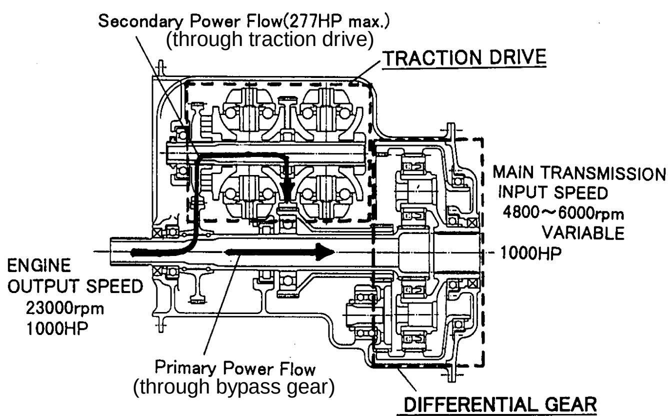

Figure 7 – Power Split Module

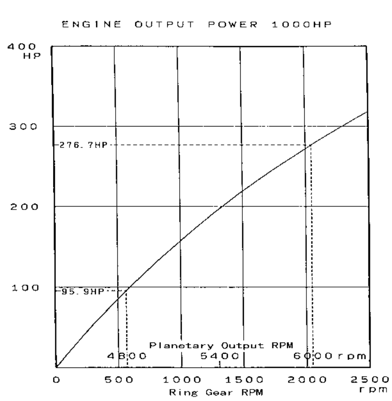

Figure 8 – Power Flow into Traction Drive

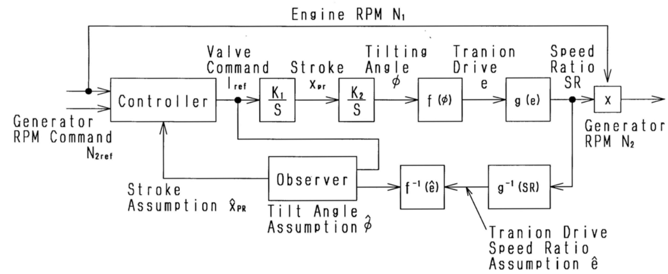

Figure 9 – Sensor-less Control Block Diagram

Environmental Conditions

Several unique environmental conditions as below have to be considered to develop aircraft equipment :

1) Wide range of attitude conditions including minus G and zero G conditions.
2) Low atmospheric pressure as low as 0.15atm (corresponds to 13,000ft of altitude)
3) Wide atmospheric temperature range: minus 54℃ up to approximately plus 200℃.

To contend with these severe environmental conditions, the following were newly developed:

1) All attitude oil system including the inversion sump and scavenge pump.
2) Hermetic type mechanical seal to keep the inside pressure positive.
3) Traction fluid which has both low viscosity at low temperature and a high traction coefficient at high temperature.

High Response

It is a requirement that the modern IDGs should have a no break power transfer (NBPT) capability. To achieve NBPT, a electronic servo valve control was employed instead of a conventional mechanical feedback. This realized a precise phase matching, which is necessary to conduct NBPT, between the AC power from Auxiliary Power Unit (APU) or Ground Power Unit (GPU) and the AC power from the IDG.

The electronic servo control brings another benefit : this makes it easier to change the control parameter and can reduce the development time period and cost.

On the other hand, a pre-heating device should be provisioned to cope with low temperature starting.

DEVELOPMENT TESTS

To overcome the technical barriers described in the previous section, a series of development/qualification tests have been conducted. An overview of them are presented in the following sub-sections.

High Speed Traction Drive Element Test

To confirm the viability of 23,000rpm traction drive CVT, an experimental model shown in Figure 10 was manufactured. In this model, the low spin configuration, the ceramic bearing and the servo valve control were incorporated. The traction drive element size was determined assuming that this will be applied to the variable rotor speed transmission. The maximum input speed is 23,000rpm, speed ratio range is 0.5 to 2.0 and the rated torque is 200Nm. The peripheral speed of the rotating elements reached 100m/sec. Table 1 shows the major data.

With this experimental model a lot of effective test data on high speed traction drive were accumulated. Figure 11 shows one test result which proved its high response capability at high speed.[4]

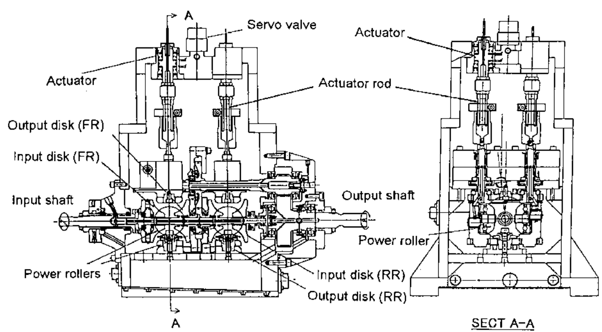

Figure 10— High Speed Traction Drive Test Rig

RIG TEST MODEL SPECIFICATIONS

Transmitted horse power	276 HP
Variable speed range(N1/N2)	0.5 to 2
Input rotational speed N1	Up to 23000 rpm
Output rotational speed N2	11500 rpm to 46000 rpm (when N1 is 23000 rpm)
Tilt angle φ	28.4 to 71.6 degree
Variable speed control	Output rotational speed feedback PID control

TRACTION DRIVE SPECIFICATIONS

R_{12}	36 mm
R_{22}	28.8 mm
θ_0	50 degrees
k_0	0.444
e_s	0.5 to 2

Table1— Major Data of High Speed Traction Drive

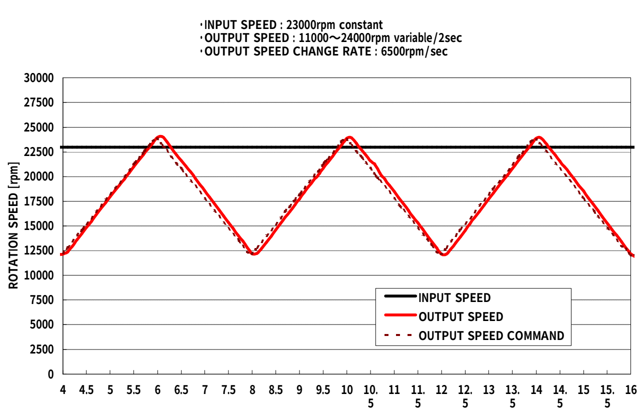

Fig.11 —Triangular Speed Change

1,000hp Power Split System Test

To prove the viability of the power split system an experimental model which corresponds to the CVT module of the helicopter variable rotor speed transmission was manufactured. Figure 12 shows the picture of the model.

This model proved the high mechanical efficiency and effectiveness of the power split system with no torque re-circulation gear ratio [7].

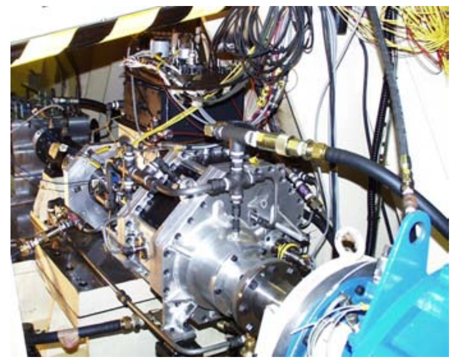

Fig.12— Full Scale Model Test Specimen

Development of Traction Drive IDG (T-IDG®)

Employing the technologies developed to date, e.g. high speed traction drive technology, power split mechanism, the oil system compatible with the severe environmental conditions and the sensor-less electro-servo control, the development of an all new concept IDG dubbed "T-IDG® " was started. Thanks to these innovative technologies, the T-IDG® is featured with high efficiency and high reliability.[8]

The current model T-IDG® was developed aiming at medium class passenger aircraft. So the power rating was set at 90kVA continuous. The picture of it is shown in Figure 13. The leading particulars are shown in Table2. A cutaway is shown in Figure14. It is compatible with 4,500~9,200rpm variable input speed whereas it drives the generator rotor with 24,000 rpm constant and produces 400Hz constant frequency AC. So the relationship between the input and output is opposite to the helicopter application where the input speed is constant and output is variable.

Figure 13 —T-IDG®

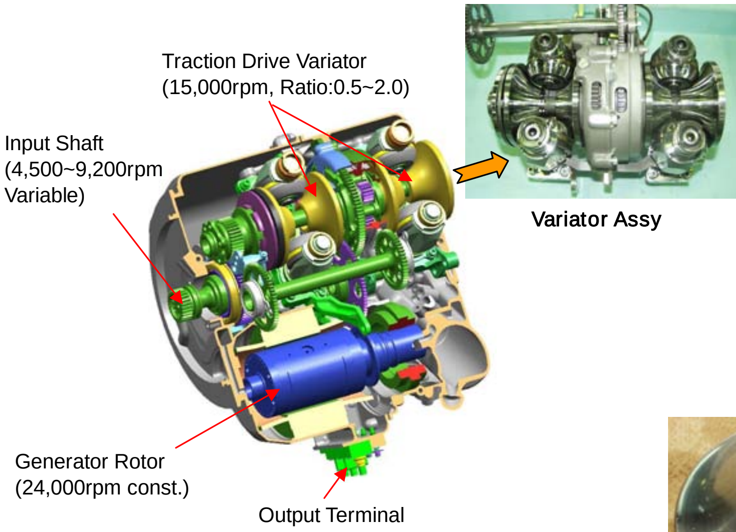

Figure 14 —T-IDG® Cutaway

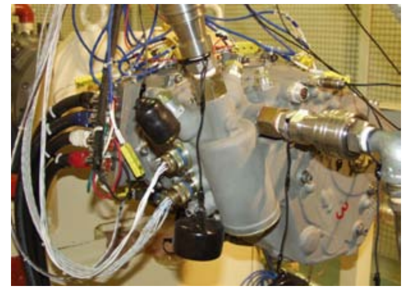

Figure 15 —Endurance Test Setup

Figure 16 —Traction Drive Elements after Endurance Test

Table 2 T-IDG® Data

- Cont.Rating：90kVA
- 5 min. Rating：112.5kVA
- 5 sec. Rating : 150kVA
- Frequency：400±5Hz(3ϕ)
- Voltage：115/200V
- Size：375L×460W×330Hmm
- Weight：54.0kgf(dry)

The following extensive development/qualification tests were performed to develop the T-IDG®.

- Electric performance
- Endurance test
- Environmental tests such as high/low temperature, high altitude, vibration, sand/dust test.
- Electronic Magnetic Interference (EMI) test
- Attitude test
- Engine Installation Test using actual aircraft engine

These tests have proven that the T-IDG® meets all the customer requirements including MIL-STD-704E and also its superiorities in efficiency and reliability.

Some of these tests are overviewed in the following sub-sections:

Endurance Test: An 1,000 hour endurance test with accelerated loading condition was successfully completed. The test setup is shown in Figure15. The traction drive element after the test is shown in Figure 16. The condition is so excellent that no track lines were observed on the disc.

Low Temperature/High Altitude Test: Using a chamber as shown in Figure 17, Low Temperature/High Altitude Test was conducted with the simultaneous temperature/pressure condition of –54℃ and 0.15atm.

Attitude Test: In addition to normal pitch/roll test, complete minus G condition test was successfully completed. Figure 18 shows the attitude test with –30deg pitch down condition.

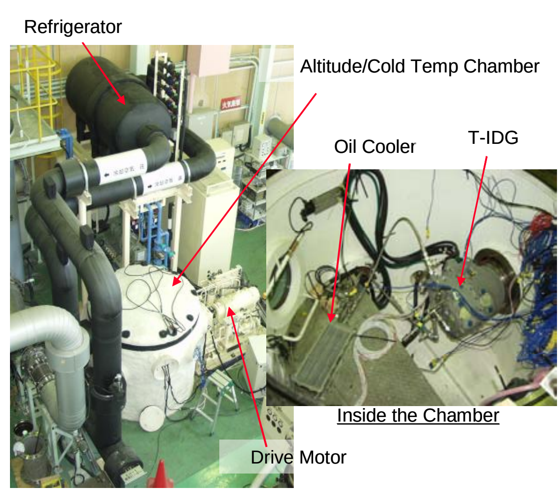

Fig.17 Low Temp./Altitude Test Setup

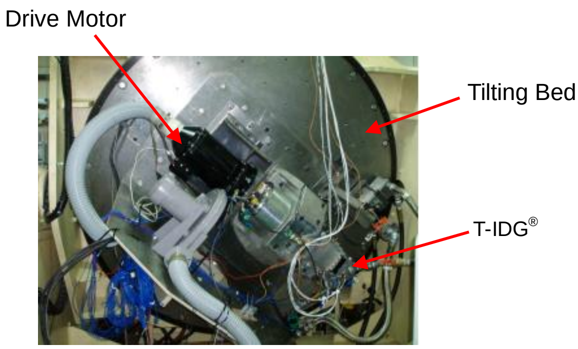

Figure 18 Attitude Test

Engine Installation Test: The T-IDG® was installed on a Rolls-Royce Trent 500 large turbo-fan engine (see Figure19). This proved the compatibility with the actual engine installation conditions.

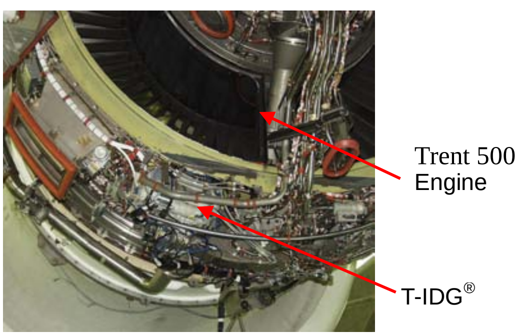

Figure 19 Engine Installation Test

Performance Data: Figure 20 shows the data which prove the excellent controllability of the T-IDG®. The IDG input speed was changed rapidly but the generator speed was controlled well within the MIL-STD-704E allowable limit.

Figure 21 shows the heat rejection of the T-IDG® when it generates 30,60 and 90kW electric power. The overall efficiency including generator loss and pump driving loss exceeds 80%, which is the highest level in this class.

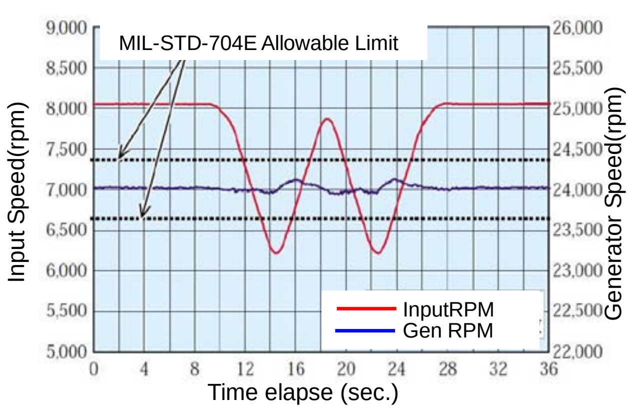

Figure 20 Input Speed Maneuver Test

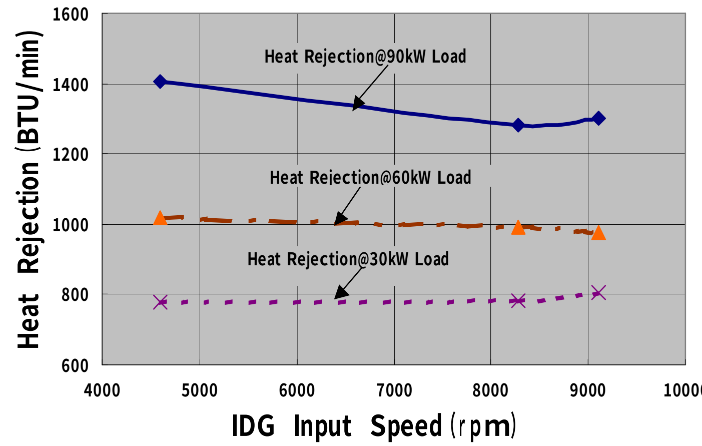

Figure 21 T-IDG Heat Rejection

CONCLUDING REMARKS

To realize the traction drive CVT for aircraft applications, extensive development efforts have been conducted. As the result, the high speed traction drive technology, power split mechanism, the oil system compatible with the severe environmental conditions and the sensor-less electro-servo control have been developed. Employing these innovative technologies, an all new concept IDG dubbed "T-IDG® " was developed and selected for the Japanese military aircraft. To verify and improve the reliability a long term endurance test is being conducted (total 100,000+ hours using 5 IDGs).

Studies to apply this CVT technology to other aircraft equipment will be continued.

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