# High Speed Submerged Motor Pump for Liquefied Natural Gas Service Supported by Magnetic Bearings

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## ABSTRACT

Submerged motor pumps for liquefied natural gas service are usually supported by special ball bearings[1], but the life of these bearings is not long enough. To improve this problem we have developed a high speed submerged motor pump supported by active magnetic bearings for liquefied natural gas service. If we could decrease the number of impellers because of the high rotating speed of the rotor, then the pump casing can become smaller. The magnetic bearings of this submerged motor pump are five-axis type active magnetic bearings. To control the rotor in the thrust direction, we used magnetic bearings and the liquid thrust equalizing mechanism (TEM). The mass of the rotor of this high speed submerged motor pump is about 50 kg. The designated speed of the rotor is about 16400 rpm. The magnetic bearings facilitated stable rotor rotation in LNG, and the magnetic bearings kept good stability under the cavitation pump condition. Further, we could rotate the rotor under closing flow rate conditions associated with complicated flow forces.

## 1. INTRODUCTION

Magnetic bearings allow the rotor to rotate in a non-contact state, which permits high-speed rotation with minimized energy loss. This property means the rotary machinery can be made smaller, and provides for an extended service life, better preventive maintenance, and no friction-related mechanical damage. Also, the magnetic bearings do not show poor magnetic properties even at low temperatures. Therefore, these magnetic bearings are very suitable for use in low-temperature rotary machinery.

In order to obtain stable, replaceable resources and to protect the environment, the demand for LNG, a low-temperature, clean, energy-producing gas that produces no sulfur dioxide when burned, has increased recently. The submerged motor pumps is one of the important pieces of equipment in LNG plants, and current submerged motor pumps tend to use ball bearings designed with special consideration for the properties of LNG. However, extreme operating conditions, such as where operations must take place in media with extremely low temperatures and viscosity, have raised the problem of shorter service lives of ball bearings. That necessitates further improvements to provide satisfactory improvements in maintenance.

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Utilizing magnetic bearings which allow non-contact rotor support might be a solution to this problem. Using magnetic bearings in submerged motor pumps would increase pump velocity and reduce manufacturing costs as a result of the reduction in pump size, in addition to sharply cutting maintenance costs through extending the service life of the bearings.

Then, we prepared a high speed submerged motor pump which uses magnetic bearings and carried out the operation test by using LNG to check the characteristics of the magnetic bearings and the performance of the pump. Favorable results were obtained, and they are presented in this paper.

## 2. PUMP OUTLINE

### 2.1 PUMP SPECIFICATIONS

| | |
|---|---|
| Type of pump: | Suction–vessel vertical–shaft centrifugal pump |
| Liquid: | LNG (Liquid Natural Gas) |
| Temperature of liquid: | –162°C |
| Density of liquid: | 450 $kg/m^3$ |
| Flow rate: | 24 $m^3/hr$ |
| Pump head: | 450 m |
| Rotating speed: | 16400 $min^{-1}$ |
| Rated motor power: | 37 kW |

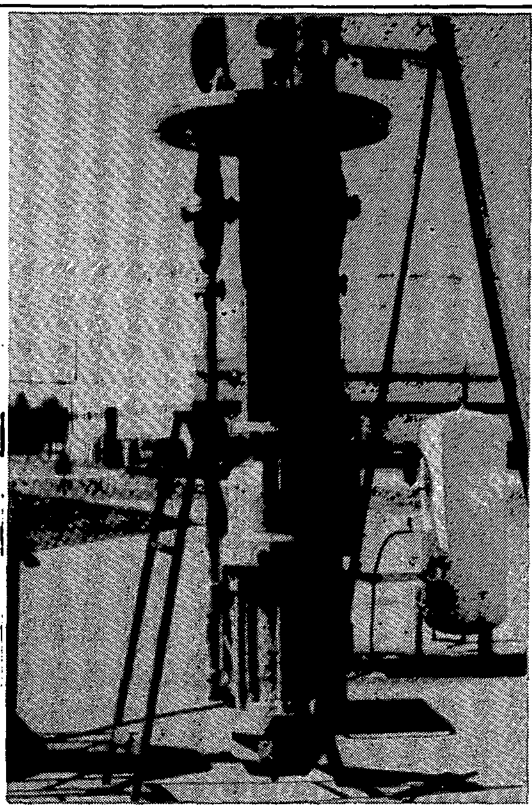

Photo.1. Outside view of the submerged motor pump

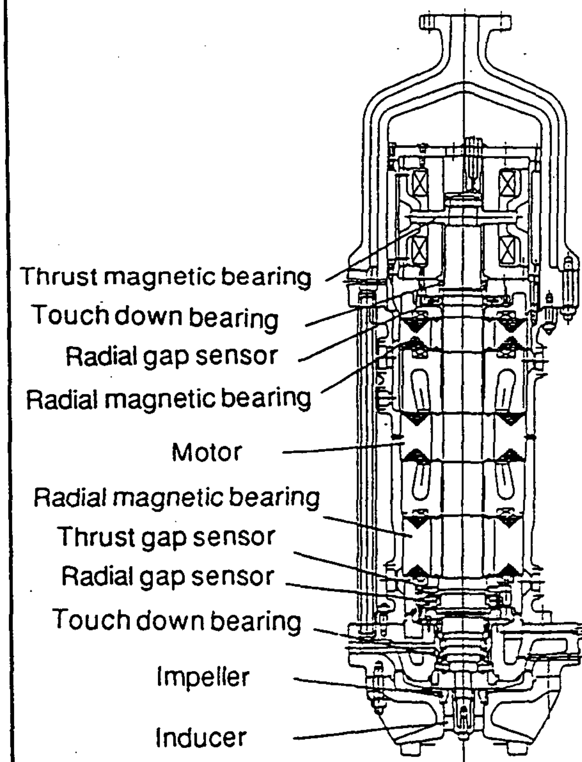


Figure.1. Sectional view of the submerged motor pump

### 2.2 CONSTRUCTION OF PUMP

Photo 1 shows the appearance of the pump, and Fig. 1 illustrates the cross-sectional structure. The casing and impeller are made of aluminum alloy casting, and the main shaft is 9% Ni-steel.

### 2.3 CONSTRUCTION FEATURES

#### Bearings

A five-axis control-type magnetic bearing system including radial magnetic bearings in the upper and lower parts of the motor rotor, and thrust magnetic bearing at the top of the shaft is used. While the main role of the thrust magnetic bearing is to receive the floating force of the rotating rotor. The axis thrust force is usually equalized by the self-equalizing mechanism (TEM), which utilizes the hydraulic power described later. In addition, touchdown bearings are arranged adjacent to the radial magnetic bearings for protection. More will be said about the magnetic bearings soon.

#### Axis thrust equalizing method

A hydraulically operated self-thrust equalizing mechanism (TEM) is employed for balancing the axis thrust load during operation. The TEM is a system which combines what are known as a balance piston and balance disk. Although it is very simple in construction, the hydraulic thrust forces produced by the impeller are equalized.

#### Motor and inverter

A three phase high-frequency induction motor is used. The rotating speed of the motor is controlled by an inverter.

The motor and the magnetic bearings are forcibly cooled by circulating LNG. By controlling the flow of cooling liquid between the rotor and stator, a film-boiling condition is produced on the surface of the rotor which markedly reduces the rotor's friction loss.

## 3. GENERAL FEATURES OF MAGNETIC BEARINGS

The five-axis control-type magnetic bearing system used in this pump can detect relative displacement between the rotor and stator, control the five degrees of freedom by use of electromagnets, and support the rotor in a non-contact state.

The specifications and components of the magnetic bearings for the pump used in the LNG operating test are as follows:

### 3.1 MAGNETIC BEARING COMPONENTS

Each magnetic bearing consists of the following components:

1. A body for the magnetic bearing and relative displacement sensor
2. A sensor amplifier
3. A phase-compensating circuit unit
4. A servo amplifier
5. An explosion-proof box for the sensor amplifier

## 3.2 MAGNETIC BEARINGS

As described later, the rotor has natural frequencies, 1st and 2nd natural frequencies are 366Hz and 859Hz respectively. The maximum rotating speed is 16400 min$^{-1}$ (273Hz). It is therefore considered as a rigid rotor. Its mass is approximately 50 kg.

The radial hydraulic forces on the impeller and the inducer are as follows:

Estimated static hydraulic force: approx. 500 N
Estimated dynamic hydraulic force: approx. 800 N

The outer diameter of the radial bearing rotor core is 115 mm, and the radial clearances of the radial baring are 0.25 mm (lower part) and 0.3 mm (upper part).

The major role of the thrust bearing is to float the roter when the rotor is starting. Meanwhile, if the TEM mechanism is not operating, the bearing also works as an auxiliary device while rotating at low-speed and producing cavitation. To adapt itself to the longitudinal change in the casing and rotor caused by temperature differences between ordinary temperatures and low temperatures, the clearance of the thrust bearing is made larger (2 mm on one side) than that of the common thrust magnetic bearing.

## 3.3 SENSOR AMPLIFIER

In the case of use with liquefied natural gas, the compensatory circuit unit and servo amplifier must be installed in the safety zone as a countermeasure against an explosion in emergencies. For this reason, these components of equipment were located 200 m from the pump body. However, it is not practical to transmit the sensor voltage output signals over a distance of 200 m without attenuation. Therefore, the sensor amplifier was placed in an explosion-proof box adjacent to the pump. By using a system in which V/A and A/V conversion of the sensor output signal could be performed serially by the sensor amplifier and compensatory circuit respectively, loss of signal intensity was eliminated throughout the transmission line.

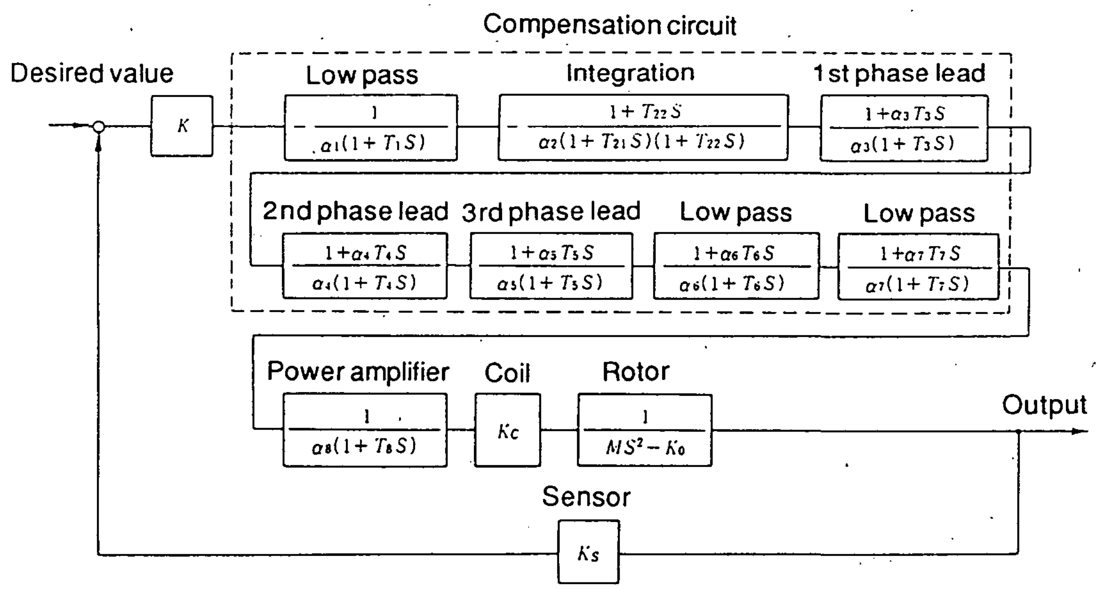


Figure.2 Block diagram of system

### 3.4 COMPENSATORY CIRCUIT UNIT

Fig. 2 shows a block diagram of the magnetic bearing system. The compensatory circuit consists of a low–pass filter (which removes high frequency noise), an integral circuit (which increases the static rigidity of the bearings) and a phase–lead circuit (which stabilizes the system).

Fig. 3 shows the results of root locus analysis of the impeller radial bearing. It can be seen that the real part of the root is in the minus zone at the design point, showing that the system is stabilized.

### 3.5 SERVO AMPLIFIER

This servo amplifier is of the PWM type and can minimize power loss; its voltage is 80 volts.

### 3.6 COUNTERMEASURES AGAINST EXPLOSIONS IN EMERGENCY SITUATIONS

The sensor amplifier placed near the pump is placed in an explosion–proof box charged with $N_2$–gas. Also, to prevent the liquefied natural gas from leaking to the outside, the junction box and feed through are used for wiring the control lead and sensor lead.

## 4. NATURAL FREQUENCY OF ROTOR

Since the tested pump rotated as a rigid rotor, the first natural bending frequency had to be higher than the rotational frequency. So first, the natural frequency of the rotor was measured and Fig. 4 shows the first bending natural mode shape and frequency. Next, rotor dynamics was analyzed to check the change in natural frequency during rotation. The results of this analysis are shown in Fig. 5. The first bending natural frequency when not rotating was 330 Hz during this analysis, and 366 Hz during observation. Therefore, at the rated frequency of revolution of 16400 $min^{-1}$, the rotor functioned as a rigid rotor.

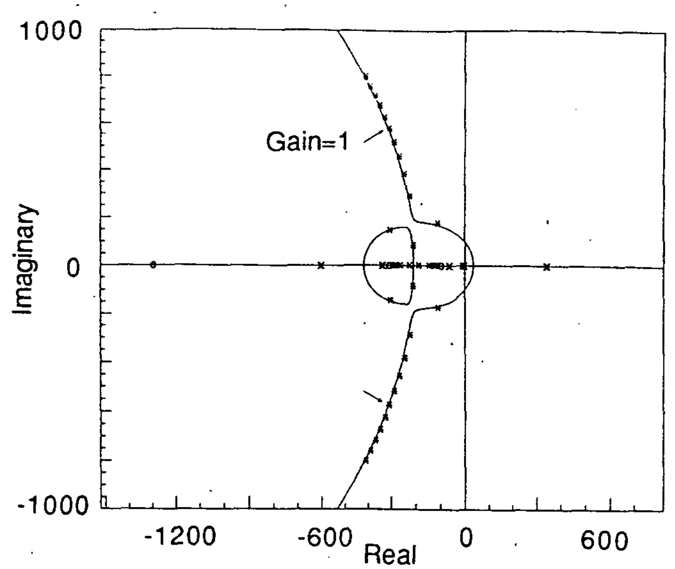


Figure.3. Root locus analysis

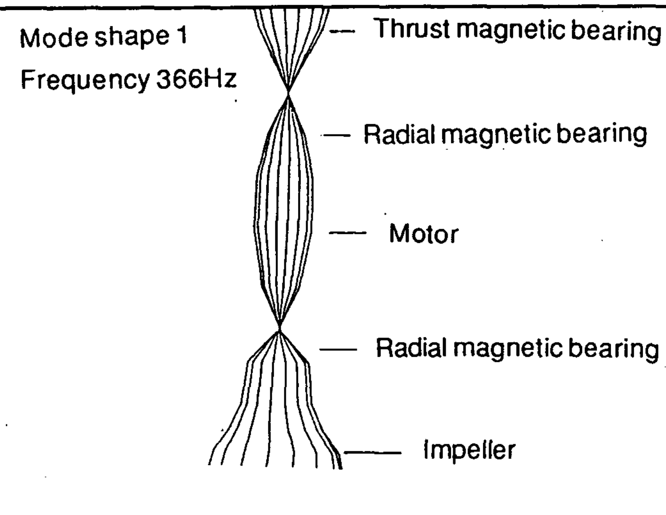


Figure.4. 1st natural frequency and mode shape

# 5. TEST RESULTS

## 5.1 UNDERWATER TEST

The rotating test was performed in water before it was performed in LNG in order to check the various properties of the magnetic bearings. In the underwater test it was necessary to install mechanical seals to prevent water from entering the magnetic bearings. We also modified the LNG test pump during preparation of the test pump by providing mechanical seals. Both pumps had almost the same shape and dimensions. The rated frequency of revolutions was 12600 min$^{-1}$. The following are all of the data that were not measured in the above-mentioned LNG test. Figs. 6 to 8 give examples obtained by measuring waveforms of both the sensor signal and magnetizing electric coil current when rotor was floated by the magnetic bearings. Maximum electric currents of approximately 12A and 8A flowed through the control coils of the impeller magnetic bearings and the upper (anti-impeller) magnetic bearings respectively. Also, a maximum electric current of 30A flowed through the control coil of the thrust magnetic bearing.

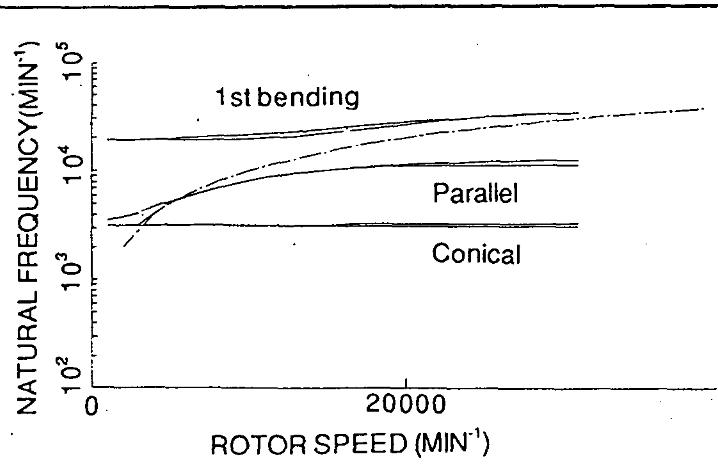


Figure.5. Natural frequency of rotating rotor

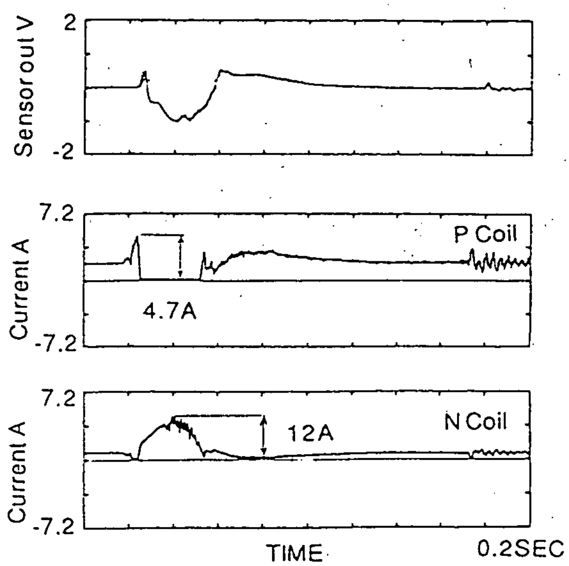


Figure.6.

Waveforms of the electric curent (Impeller side radial magnetic bearing)

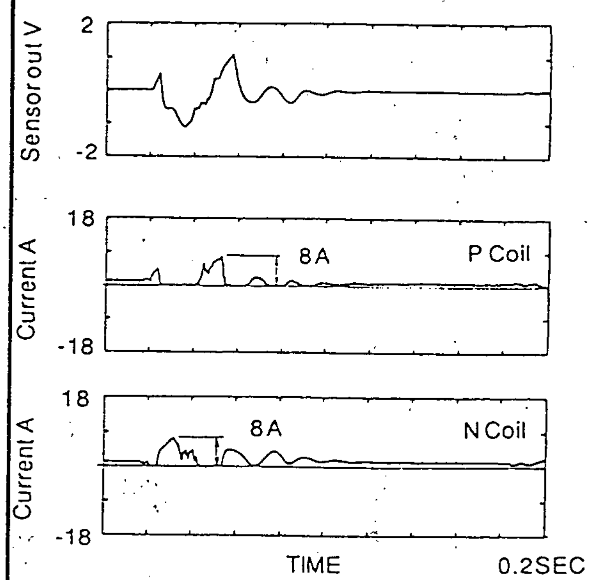


Figure.7.

Waveforms of the elctric current (upper side radial magnetic bearing)

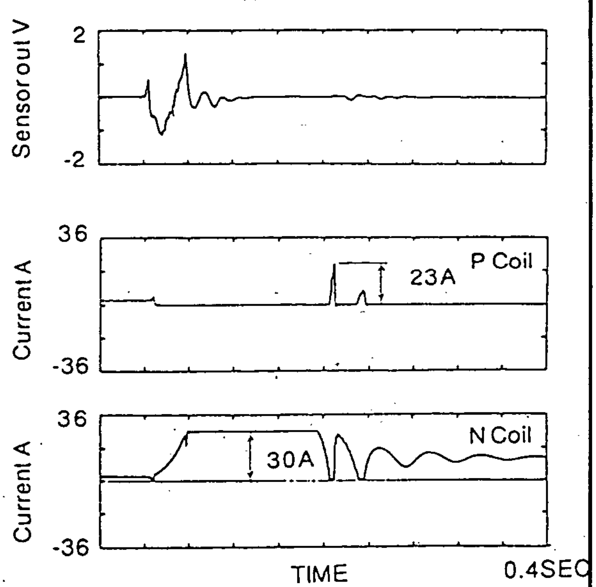


Figure.8.

Waveforms of the elctric current (Thrust magnetic bearing)

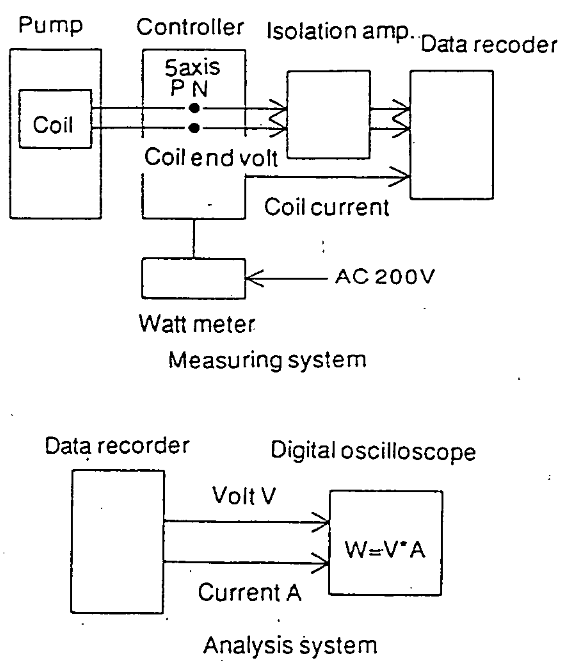


Figure.9.

Measuring and analysis system

In the rotating speed acceleration test, a steady increase in the frequency of revolutions was observed until the rated frequency of revolutions, 12600 $min^{-1}$, was reached. Moreover, in the diversified flow tests and NPSH tests, when it was expected that there would be large, external, hydraulic disturbance of the rotor, stable control of the rotor was verified. (These results led us to the conclusion that it would be possible to use magnetic bearings in a submerged LNG motor pump, so subsequent tests were conducted in liquefied natural gas.) Thus, we measured the electric power loss in the magnetic bearing body excluding the controller and servo amplifier by the method shown in Fig. 9, and found that only about 700 W was lost at the rated frequency of revolutions of 12600 $min^{-1}$.

## 5.2 TEST IN LNG

Fig. 10 shows a schematic drawing of the testing apparatus used to test the LNG pump in LNG. This testing apparatus was of a circulating closed loop type with a storage tank. Operating temperature of the bearing stator was about −162°C to −157°C.

Fig. 11 shows the open loop transfer functions of the impeller side radial bearing measured while floating. In order to stabilize the magnetic bearings, they were provided with a generous gain margin and a phase margin for the open loop transfer function, which showed that this system is stable. The same properties were obtained for the other bearings.

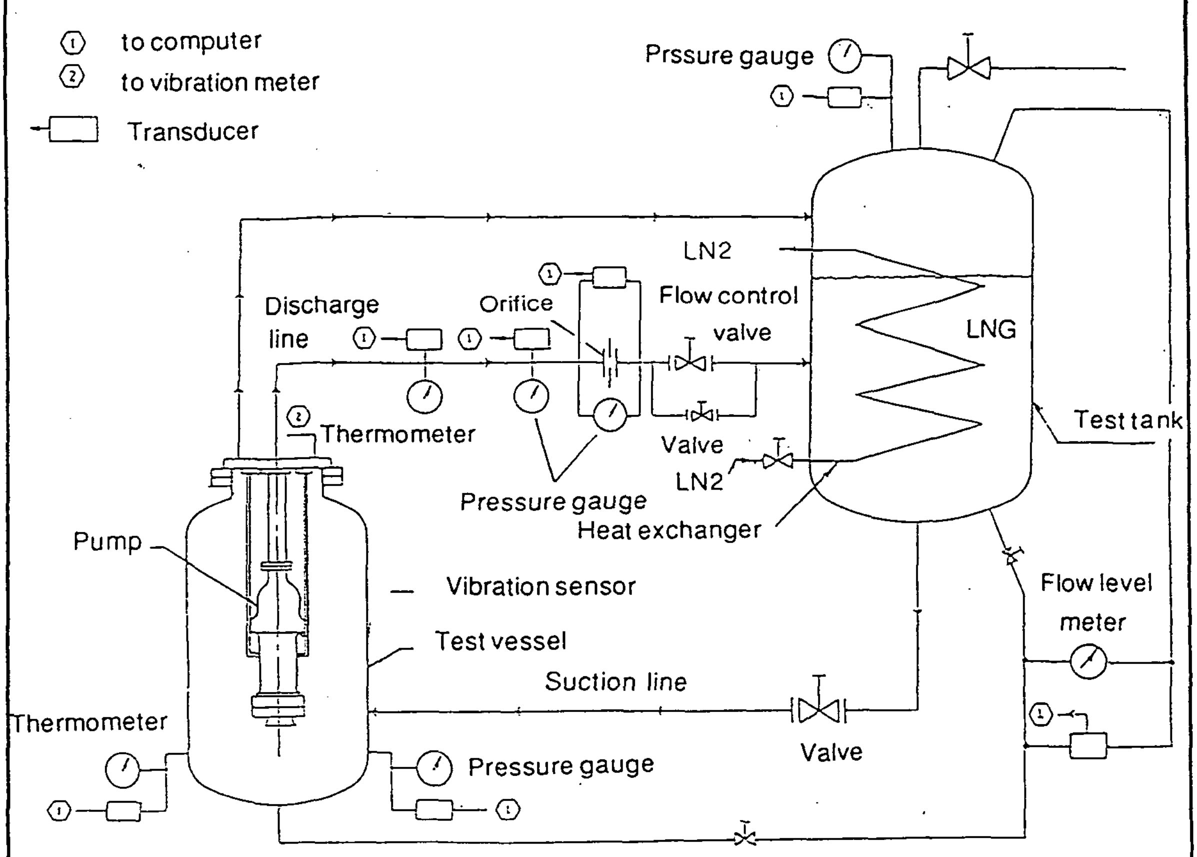


Figure.10. Pump test stand

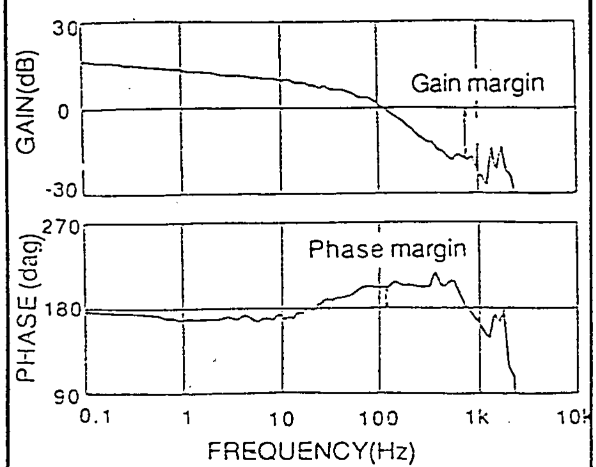


Figure.11. Open loop chracteristics

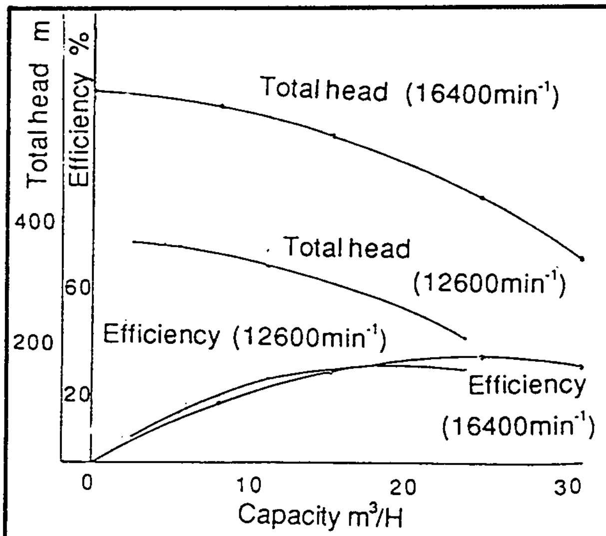


Figure.13. Pump performance curves

Fig. 12 illustrates the vibration frequency spectra and the loci of the rotor whirl (Lissajous figures) of the impeller side radial bearings measured as the speed of rotation increased from 6000 $min^{-1}$ to $16400^{-1}$. The maximum whirl of the rotor was 40μmp-p. It was also confirmed that the thrust magnetic bearing exerted axial control in low-speed, low-pressure conditions, as TEM did in high-speed, high-pressure conditions.

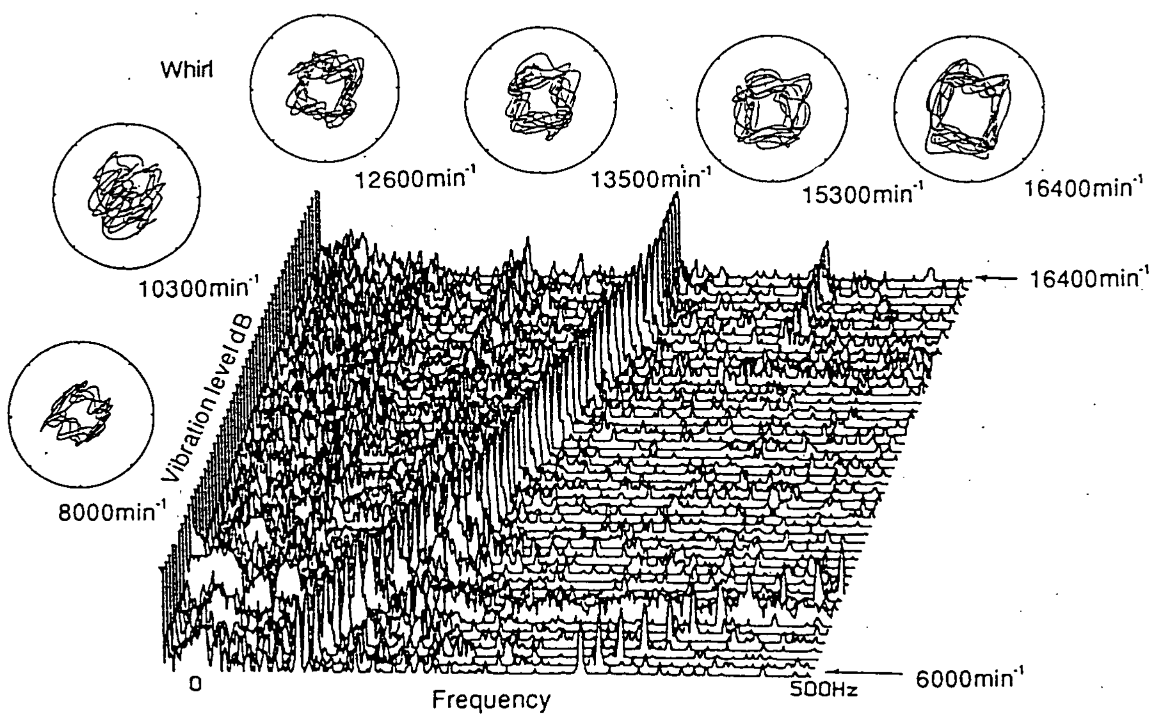


Figure.12. Vibration of impeller side radial sensor

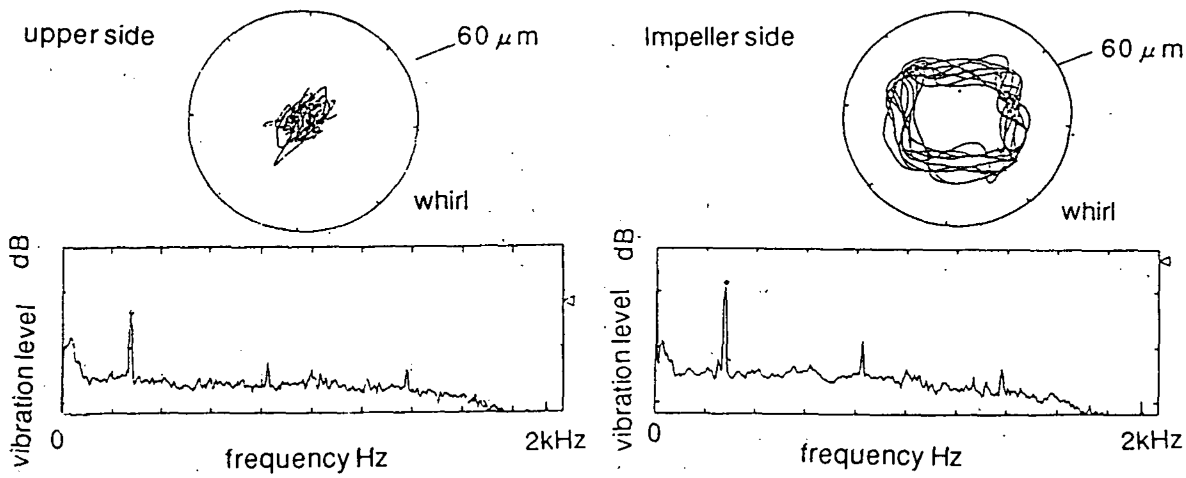


Figure.14. Whirl and Vibration of the rotor
(Cavitation condition at 16400min$^{-1}$)

The performance of the pump is shown in Fig. 13. Fig. 14 shows the vibration spectra and the loci of the rotor whirl when the lowered rate of total pump head was 10% in the NPSH test with a frequency of revolutions of 16400 min$^{-1}$ and in the most efficient conditions. In these conditions, maximum whirl was 35μm p-p on the impeller side and 10μm p-p on the upper side. Although some unstable loci of the rotor whirl were observed, it was noted that no-discharge operations might also be practicable.

## 6. CONCLUSION

From the operating test using the LNG pump with a five-axis control type magnetic bearing system and conducted in the actual liquids, we resolved the following:

(1) Even in liquids with temperatures as low as −162°C, the magnetic bearings and their displacement sensor can operate satisfactorily without problems.

(2) Magnetic bearings can operate stably despite the high frequency dynamics loads generated b a high speed impeller pumping an incompressible fluid.

(3) In liquefied gas service facilities, it is necessary to place control devices with magnetic bearings in safety zones as a countermeasure against explosions in emergency situations. When the control devices and the sensor pre-amplifier setted near to the pump are placed a long distance from each other, satisfactory results can be obtained by adopting appropriate signal transmission systems.

Using this test in LNG, it was clear that the pump speed could be increased, the pump could be made smaller in size, and a sharp reduction in maintenance costs could be expected if magnetic bearings are used in LNG pumps.

We have succeeded in manufacturing a submerged motor pump which uses magnetic bearings and at the same time increases the range of applications in the market for extremely low-temperature devices.

## REFERENCES

1. Terashima, K., Matsumura, F., September 1987. "Cryogenic Submerged Motor Pumps." EBARA ENGINEERING REVIEW, 138:39-44.