Helium Cold Compressor with Active Magnetic Bearings

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1.Abstract

The number of **Active Magnetic Bearing** (AMB) equipped rotating machines has been increasing remarkably in the last few years (1). It can be pointed out that the turbo molecular vacuum pump (TMP) is the most successful application for AMB system as a series production. Furthermore, machine-tool spindle (2), flywheel energy storage system (3), general-purpose gas blower and other turbo machinery are also interesting application fields for AMB.

In 1997, Ishikawajima heavy Industry (IHI) installed helium cold compressor prototype (4) (5) (6) with 5 axes controlled AMB spindle produced by KOYO Seiko Co., LTD in the CERN (Geneva, Switzerland). In this paper the above mentioned 5 axes controlled AMB spindle are reported associating to “Digitally controlled AMB”.

2. Helium cold compressor prototype

The Large Hadron Collider (LHC) project has been progressed at CERN, Geneva, Switzerland, where high-energy particle accelerator with 26.7-km circumference is under construction. In such facilities, development of the technology of large-capacity refrigeration at super-fluid helium temperature is essential for high-field super-conducting magnets of LHC cryogenic system. The helium cold compressor is a key component for the system requiring helium refrigeration cooling down to 1.8K.

CERN ‘s specification for the cold compressor prototype (CCP) is shown bellow. It is noticeable that, for this relatively small-flow prototype, the thermal design to minimize the heat in-leaks from outside is very important.

Table 1 Main Specification of CCP required by CERN

Helium flow-rate	[g/sec]	18
Suction pressure	[kPa]	1
Discharge pressure	[kPa]	3
Compression Ratio	-------	3
Helium suction temperature	[K]	3.5 to 4.4
Adiabatic efficiency	-------	60% or more

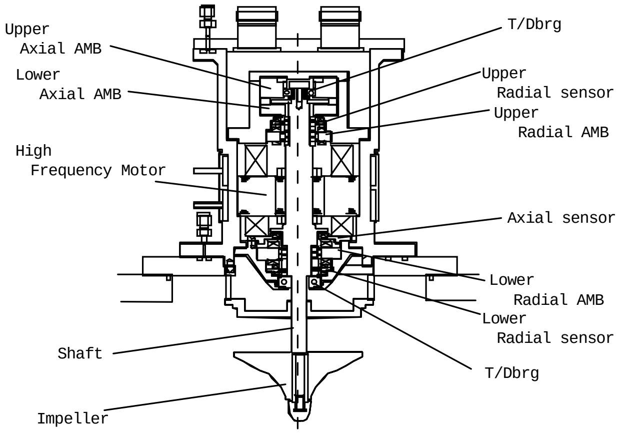

Fig 1 Crossection of Helium Cold Compressor 18gr/sec

Fig 1 shows cross-sectional view of the CCP. The compressor can be classified as a centrifugal compressor adopting the 3-D (un-shrouded axial-centrifugal) impellers of an outer diameter of 120mm. The shaft having 3-phase induction motor, which can drive up to 26,500rpm, is installed in vertical position. The radial AMBs are locating both end of the motor element and axial AMB is placed upper side of the shaft. The motor and entire AMB components are located at ambient temperature to prevent the defect or the failure of wire to keep high reliability.

The touch down bearings are used in lower side of the shaft locating near the impeller and in upper side of the shaft locating at the inside of axial AMB.

The thermal anchor using liquid-nitrogen (80K) is placed between the motor-AMB section at ambient temperature and impeller at 4K to absorb heat in-leaks. Additionally the honey - comb block is installed between the thermal anchor and impeller, and ambient section to avoid a convection of helium. Since the thermal conductivity of helium gas is lower than the solid heat insulation material, stationary helium gas can be used as good heat insulator.

In the case of 5 axes (or 5 degree of freedom) controlled AMB system, a minimum of 5 sets of sensors have to be installed corresponding to the number of mentioned control axes. So as to eliminate the temperature drifting of the displacement sensor, 2 sensors located opposite each other are used for 1 radial direction. For the same purpose, one temperature compensation sensor (dummy sensor) is also used in the axial direction. Consequently, totally 10 displacement sensors are recommended to be installed in a 5 axes controlled AMB system. The designed specification of compressor and AMB for CCP are listed in Table 2.

Table 2 The compressor and AMB specification for CCP

Main specification of Compressor motor		
Maximum speed	26,500 [rpm] (442 [Hz])	
Acceralation time	60[sec] （0 ～26,500[rpm]）	
Motor power	1.0 Kw / 26,500 rpm	
Impeller diameter	120 [mm]	
Rotor mass	1.8 [Kgr]	
Radial Load	（Negative stiffness of the motor）	
Axial Load	60 [N]	
Radial Bearings	Front	Rear
Bearing diamenter	35.0 [mm]	30.0 [mm]
Air gap	0.2 [mm]	0.2 [mm]
Load capacity	120 [N]	80 [N]
Bias current	0.5 [A]	0.6 [A]
Axial Bearings		
Diameter of disc	52.0 [mm]	
Air gap	0.4 [mm]	
Load capacity	250 [N]	
Bias current	0.8 [A]	
T/D Bearings	Front	Rear
Radial gap	0.1 [mm]	0.1 [mm]
Axial gap	0.2 [mm]	0.2 [mm]

So-called non-co-location problem of sensor and electromagnet in radial AMB usually occurs due to limited space around the rotor and it could cause the entire rotor system instability especially combined with 1st and 2nd bending mode.

Using modern control theory (LQE, LQG) or robust control theory (H infinity, LMI, and etc), several studies were made and were found in the literature to overcome this problem, but it is possible to say that this is still a challenging problem.

To avoid encountering this kind of problem, in this CCP project, the Rigid-Rotor-Design method for entire shaft system was taken.

Fig 2-1 and 2-2 indicate the calculated results of first and second bending mode of the entire rotating shaft assembly by means of rotor dynamics analysis program code developed by KOYO featuring finite element method. Because the shaft has very long extension cylinder part corresponding to the mentioned thermal anchor section and honey-comb section, this resulted in “over hung rotor”.

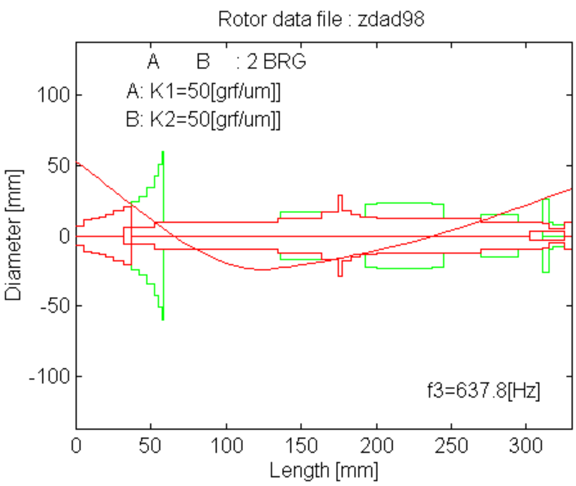

Fig2-1 1st bending mode shape and frequency of the CCP He compressor rotor

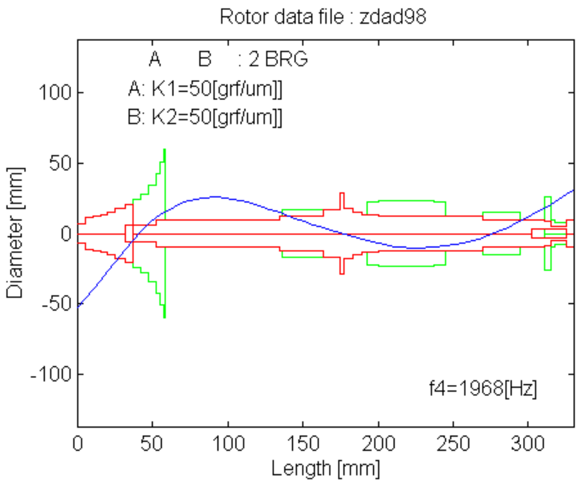

Fig2-2 2nd bending mode shape and frequency of the CCP He compressor rotor

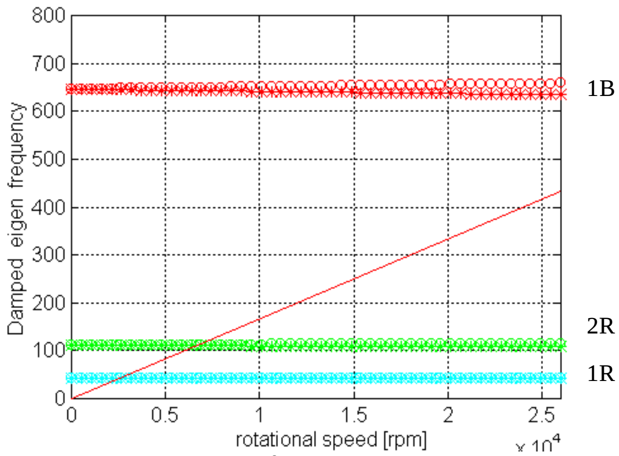

Fig3 Eigen mode Diagram of the CCP He compressor rotor

Assuming very low radial bearing stiffness, the calculated first bending mode frequency (Free-Free mode) is 638 [Hz] and second bending mode frequency is 1968 [Hz] respectively.

Nevertheless, the maximum / nominal speed of the CCP is designed 442 [Hz] / 408 [Hz], the first bending mode frequency of the shaft assembly of 638 [Hz] seemed to be high enough to accelerate the shaft and achieve the maximum speed.

The eigen mode frequency diagram is also shown in Fig 3. Because of the slender shaped rotor the gyro-scopic effect is quite small. Therefore the bending mode frequency shall be splitting not so strongly. To minimize the AMB loss consisting of copper loss in stator and eddy current loss in rotor the bias current for the radial AMBs were minimized to the limit. Resultantly, the rigid body modes are locating bellow 100 [Hz].

With an exact mathematical rotor system model derived from finite element method, gyroscopic effect by rotation and change of shrink fit amount of several parts to the main shaft due to centrifugal forces or due to heat transfer etc are carrying additional uncertainty to the mathematical model.

Fig 4 shows the specification and appearance of the AMB control unit developed for the target CCP system. The AMB controller is designed in the dimension of so-called half-rack size cabinet which is carrying an inductance sensor electronics, a fast digital controller board FDC50 (TMS320C50 fixed point DSP set with A/D and D/A converters) developed by Mecos Traxler AG, 10 channel power amplifiers, supervision electronics, and communication link board.

One of the outstanding functions of AMB is "Monitoring" (Data acquisition) of displacement, vibration and imbalance of such rotor system during operation by means of already integrated displacement sensor system. Another function of note is "Diagnosis" of the rotor system.

Thanks to digital control technology using digital signal processor (DSP) for AMB, "Monitoring" and "Diagnosis" can be carried out much easier and faster than by the classical analogue controller. Mecos Traxler AG developed the DSP communication software embedding in MATLAB, which is called MAT2TMS. Using this powerful software the serial communication (RC232C or RC485) from PC to the target DSP is also available through a modem, which even allows accessing of a system installed in an over seas location.

By means of serial communication, up-dating of newest program software for AMB controller algorithm or down loading of a new controller parameter set is also possible by burning the flash memory on the DSP board.

DSP TMS320C50 TI)
A/D 12 Bit/6 sec
D/A 12 Bit/2 sec
PMEM 64k Word FLASH
DMEM 64k Word RAM (data)

PC/Modem
Interface type RS232C serial
Maximum data rate 115.2 kBaud

Communication software
MAT2TMS (optional)

Embedding software
MATLAB@ standard

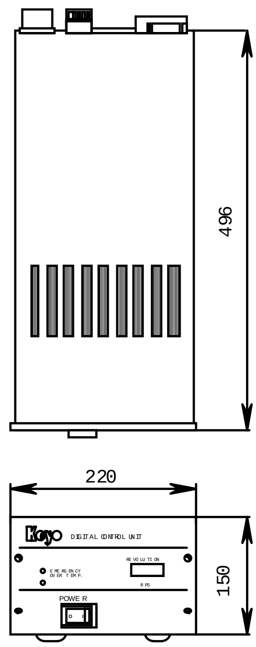

Fig4 Spec. and appearance of
the developed He cold compressor AMB control unit

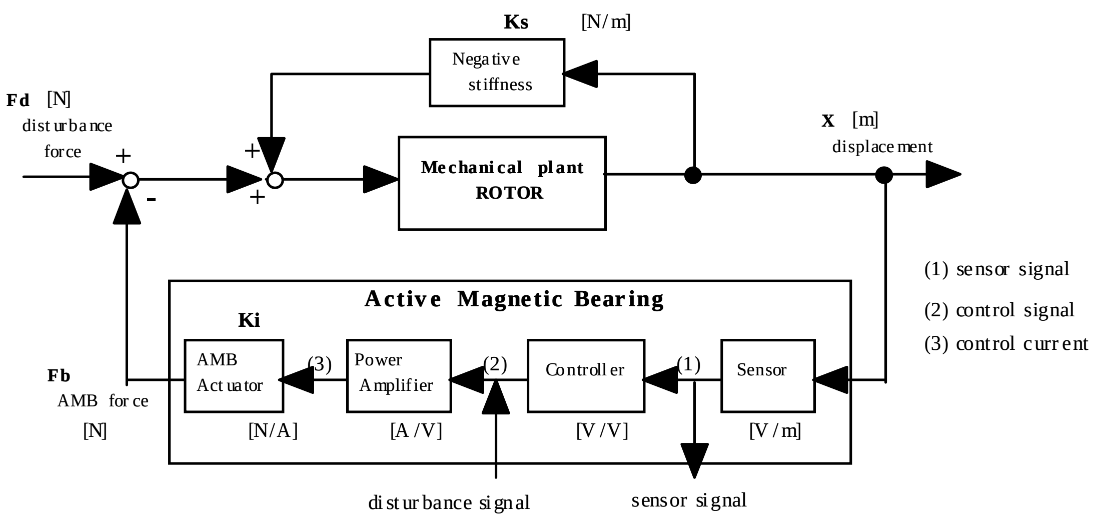

Fig5 Block diagram of Rotor system supported by AMB

Fig5 shows a block diagram of a rotor system supported by AMB with feedback control loop. Since an AMB system using the attractive force of electromagnet is essentially unstable due to so-called negative position stiffness (Ks), the feedback control is necessary to levitate the rotor stable. It is useful to describe the entire rotor system as the "system" that has the input of disturbance force(s) acting on the rotor and has displacement(s) as output of the system. Concerning all of the radial displacements and axial displacement, the rotor system can be dealt with by a multi-input multi-output (MIMO) system, 5-input 5-output system. Assuming that any coupling between radial direction (radial plant) and axial direction (axial plant) dose not exist or can be negligible, these two systems can be treated separately. Then the axial system comes to be a single input single output (SISO) system. On the other hand, the radial system comes to a 4-input 4-output system that has internal coupling according to gyroscopic effect of the rotor. Generally speaking, the main design target of AMB feedback control system is to minimize such a transfer function (= dynamic compliance = reciprocal of the dynamic stiffness).

With the DSP controller system, to minimize the computational load of the DSP, well-known de-centralized controller layout was taken for this CCP AMB system

3.Monitoring of the CCP rotor system by AMB sensors

Fig6 shows one example of the measured run-out of a rotor supported by AMB installed in CERN, Geneva, Switzerland by means of serial communication directly from PC without any other instrumental equipment or measuring devices.

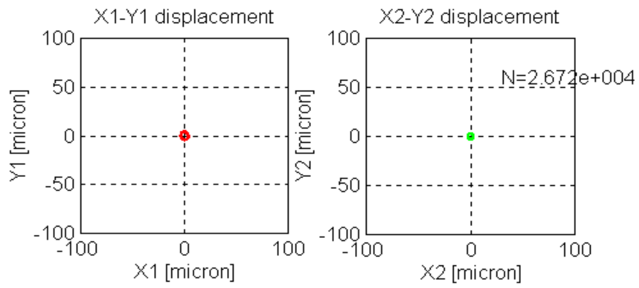

Fig6 Measured run-out of radial AMB at at 26700rpm (Heliumcompressor)

The coil current command signal as an output of the DSP controller is also very useful in obtaining information about the external force acting on the rotor system or in inspecting the mechanical gap(s) at actuators are correctly set. Fig.7 indicates one example of coil current command signals from DSP.

4.Diagnosis of the CCP rotor system by AMB actuators and sensors

The injection of the excitation signal generated by DSP and added to the desired current command signal to the power amplifier can wobble the rotor without mechanical contact by means of modulated attractive forces exerted by electromagnet. This method can be called **"Magnetic Hammering"** which can be carried out even when the rotor is rotating. The integrated displacement sensors can also easily measure the rotor system response. Now, it is very easy to calculate the transfer function of the rotor system by using already known excitation forces (given by the excitation signal of DSP) and the synchronous displacement signal component (same frequency component) to such excitation forces. Calculated transfer function of the rotor system from excitation force signal input to the displacement signal output is called sensitivity function of the controller. It is noticeable that measured sensitivity functions also carries the information of the frequency response of the sensor (in high frequency part due to the characteristics of low pass filter) and electromagnet (also in high frequency part due to the characteristics of roll off caused by eddy current effect, etc). Assuming that such high frequency response is negligible in the frequency range lower than 3KHz, measured sensitivity function is able to trace the dynamic "Compliance" of the rotor in the above frequency range.

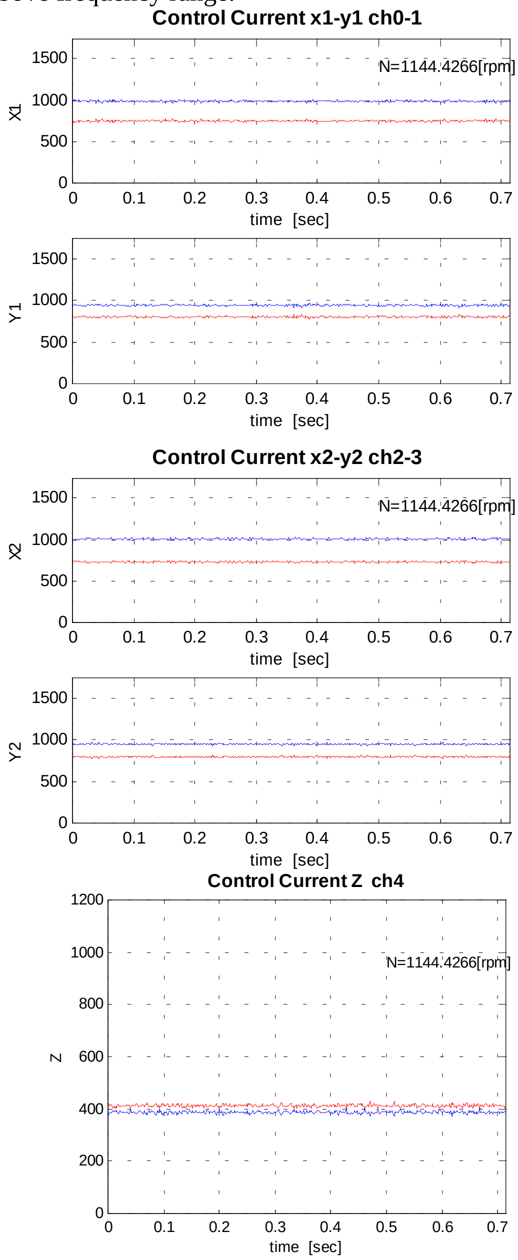

Fig7 Coil current command signal from DSP

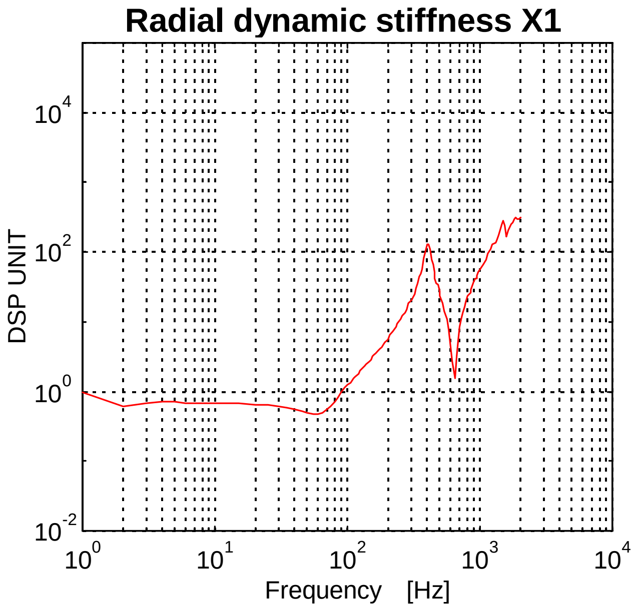

Fig5. Example of reciprocal of measured sensitivity function equivalent to dynamic stiffness at ch X1

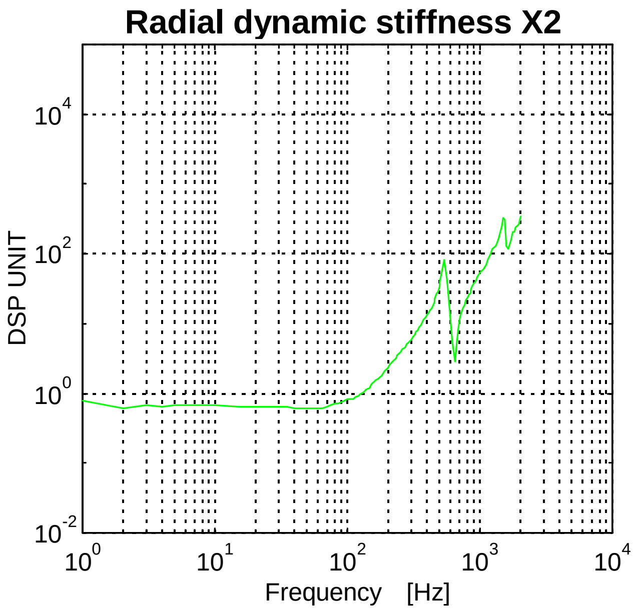

Fig6. Example of reciprocal of measured sensitivity function equivalent to dynamic stiffness at ch X2

Taking the reciprocal of measured sensitivity function gives the equivalent "Quasi Dynamic Stiffness" of the rotor. Fig5 and 6 show examples of "Quasi Dynamic Stiffness" by means of the frequency excitation method.

Due to the high damping ratio available with AMB, first and second rigid mode of the rotor system locating between 60Hz to 100Hz are well damped (typical value of damping ratio for rigid mode is 0.3 to 0.6) so that remarkable peak can not be seen any more.

On the other hand, first bending mode of the rotor locating at 640Hz in these examples is clearly measured. The sharpness of the peak corresponding to the bending mode frequency of the rotor contains important information such as damping ratio, observability of the displacement sensor for the mode shape, and so on. Generally speaking, the rotor consists of many mechanical parts such as main shaft, motor element, turbine blade, etc. These parts are fixed to the main shaft by means of shrink fitting, bolting etc. It is possible that internal material damping and friction between main shaft and above-mentioned parts contributes to the system damping and affects the damping ratio of each mode. Normally, the damping ratio of such bending mode is a quite small value (typical value of damping ratio for bending mode is 0.001 to 0.005).

From the viewpoint of diagnosis of the rotor itself, discussed sensitivity function (or its reciprocal) can be also used effectively (even for running rotor). The undesired changes or uncertainty listed above will occur in the rotor and will affect the sensitivity function curve greatly.

Such data acquisition is easily introduced by sequential batch file running on the DSP performing the measurement with pre-determined period or interval and automatic data saving / sending to the host PC / onsite PC or whatever.

5.Test at CERN

CERN LHC Division ordered three different CCP with different features and characteristics. The main difference between these CCPs is the bearing system listed bellow.

1) Static gas bearings
2) Ceramic ball bearings
3) Active magnetic bearings (IHI and KOYO)

All of the CCP had similar un-shrouded axial centrifugal impeller in size and drive was locating ambient temperature section like AMB CCP. Then the CCPs test program was carried out at CERN in March 1998. At the first time of CCP installation, AMB CCP had encountered 1.4 [KHz] vibration and this vibration seemed to be generated by rather flexible fixation of the CCP body to the chambers. But the problem was easily solved by additional controller change using above-mentioned powerful monitor and diagnosis capability and flexibility of the DSP controller.

Table 3 Comparison of CCPs

Bearings	Impeller Diameter [mm]	Nominal speed [Hz]	Drive	Thermal anchor	Impeller heat inleak	Spiral casing heat inleak	Isentropic efficiency
Static Gas	113	476	Turbine	NO	17 [W]	18[W]	0.60
Ceramic BB	118	408	Electric motor	YES	17 [W]	22 [W]	0.65
AMB	120	390	Electric motor	YES	4 [W]	3[W]	0.75

CERN LHC Division compared the CCP performance and reported Table 3 summarizes the comparison of above CCP solutions.

Due to well-designed entire compressor system made by IHI using AMB, thermal anchor, and honey-comb block, IHI CCP performed isentropic efficiency of 75% which is greater than other CCPs by 10 point.

Now, in total, CERN LHC is requiring about 20Kw of cooling power at 1.8 K, to be produced in eight stations locating around the machine circumference of 26.7 Km. For this large scale refrigeration requirement, industrial 4-stage helium cold compressors are under developing by IHI and KOYO. The new compressor system will have suction pressure of 1.5 [Kpa], discharge pressure of 60 [Kpa], pressure ratio of 40, and Helium flow-rate of 125 [gr./sec].

6.Conclusion

In this paper, 5 axes controlled AMB spindle for helium cold compressor prototype for CERN LHC Division (Geneva, Switzerland) is reported.

The helium cold compressor prototype CCP designed by IHI using digital controlled AMB was successfully tested at CERN and achieved isentropic efficiency of 75% which is 10 point better than other compressors using static gas bearings or ceramic ball bearings.

Using the measured data obtained by CCP project, now we are working on designing and producing the large-scale industrial 4-stage helium cold compressors.

7. Acknowledgement

The authors wish to acknowledge the excellent collaboration of Ishikawajima Heavy Industry in the development of this CCP project and following industrial 4-stage compressors.

8. References

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