Diagnosis of Cryogenic Pump-Motor Systems Using Vibration and Current Signature Analysis

ByeongKeun Choi*
School of Mechanical and Aerospace Engineering, The institute of Marine Industry, Gyeongsang National University, Tongyoung, Gyeongnam 650-160, Korea
HakEun Kim
Korea Gas Technology Corporation, #1179, Anjeong-Ri, Gwangdo-Myeon, Tongyoung, Gyeongnam 650-824, Korea
DongSik Gu, HyoJung Kim, HanEul Jeong
Department of Mechanical and Precision Engineering, Graduate School, Gyeongsang National University, Tongyoung, Gyeongnam 650-160, Korea

In general, to send out natural gas via a pipeline network across the nation in LNG terminal, high-pressure cryogenic pump supply highly compressed LNG to high-pressure vaporization facilities. The Number of cryogenic pumps determined the send-out amount in LNG receiving terminal. So it is main equipment at LNG production process and should be maintained on best conditions. In this paper, to find out the cause of high vibration at cryogenic pumps-motor system in LNG terminal, vibration spectrum analysis and motor current signature analysis have been performed together. Through the analysis, motor rotor bar problems are estimated by the vibration analysis and confirmed by the current analysis. So, it is demonstrated through the case study in this paper, how performing vibration analysis and current signature analysis together can reliable diagnosis rotor bar problems in pump-motor system.

Key Words : Vibration Diagnosis, High Pressure Cryogenic Pump-motor, Current Analysis, Pole Pass Frequency, Rotor Bar Pass Frequency (RBPF)

1. Introduction

Liquefied natural gas takes up six hundreds of the volume of natural gas to be reached below the boiling temperature (−162℃), which makes storage and transportation much easier. Imported liquefied natural gas is transported to ground storage tanks via pipeline using cargo pump on the LNG carrier vessel. In LNG receiving terminal, primary cryogenic pumps that are installed in the storage tanks supply the LNG to secondary pumps with 8 bar. And secondary pumps boost the LNG pressure until the 80 bar for evaporating and send-out the highly compressed natural gas via a pipeline network across the nation. The number of high-pressure cryogenic pumps determined the send-out amount in LNG receiving terminal. So it is main equipment at LNG production process and should be maintained on best conditions. Therefore, to supply the natural gas continuously in LNG receiving terminal, it is necessary for the stable maintaining of high-pressure cryogenic pump. Vibration and noise of high-pressure cryogenic pumps are monitored and managed in particular with one of the predictive maintenance skills.

High-pressure cryogenic pumps are submerged type and operated at the super cooled tempera-

* Corresponding Author,
E-mail : bgchoi@gnu.ac.kr
TEL : +82-55-640-3059; **FAX** : +82-55-640-3188
School of Mechanical and Aerospace Engineering, The institute of Marine Industry, Gyeongsang National University, Tongyoung, Gyeongnam 650-160, Korea. (Manuscript **Received** October 27, 2005; **Revised** April 25, 2006)

ture. So, it has self-lubricating at the both side bearings of rotor shaft by using the LNG. Because of the low viscous value (about 0.16 cP) of LNG, lubricating condition of cryogenic pump is a poor and bearing must be designed specially. There are some difficulties to detect the cause of the pump troubles in early stage because the bearing failure of cryogenic pump is growing rapidly with a poor lubricating condition and a high operating speed (3,600 rpm). In other words, for abnormal troubles to happen there is not enough time to analyze the root cause before pump failure. So, through the on-line monitoring system, cryogenic pump could be monitored and managed properly. Especially, due to the material property variations of cryogenic pump at super low temperature, for the study of the vibration behavior, there are some restrictions to diagnosis of pump troubles.

In this paper, to find out the abnormal vibration problem of high pressure cryogenic pump-motor system in LNG terminal, vibration and current analysis have been performed together. First, electrical problem is confirmed by vibration analysis. And then, to improve the reliability of the vibration diagnosis result, rotor influence check and current signature analysis carried out together. To modify the high beat vibration of pump-motor system, motor rotor bar is repaired and high amplitude vibration is reduced.

2. Cryogenic Pump-motor Systems

High-pressure cryogenic pumps are enclosed within a suction vessel and mounted with vessel top plate. Figure 1 shows the pump-motor system sketch and vibration measuring points. Two ball bearings are installed to support entire dynamic load of integrated shaft of pump and motor. The submerged motor is cooled and the bearings are lubricated by a predetermined portion of the LNG being pumped. To control axial loads on the anti-friction bearings, thrust-equalizing mechanism (Youn, 1996) is applied. This is adjusting automatically to produce pressure in the upper chamber sufficient to offset the upward thrust and continuous self-adjustment at “zero” thrust load over the entire. Figure 2 shows the component drawing of thrust equalizing mechanism.

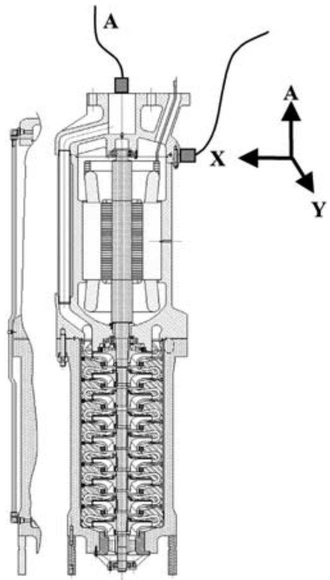

Fig. 1 Pump sketch & vibration measuring points

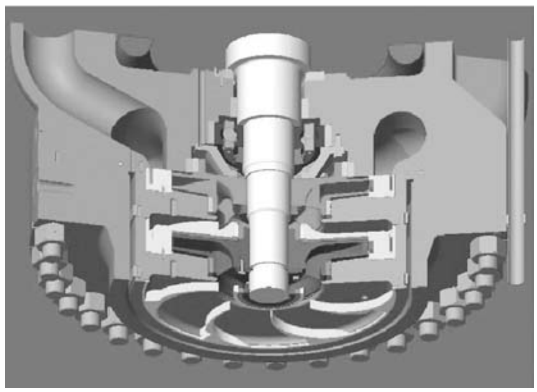

Fig. 2 Component drawing of thrust equalizing mechanism

Tables 1 and 2 shows the main specification of pump and motor. Pump is the submerged turbine type with multi stage axial diffuser, and motor is an induction type.

To detect the abnormal condition of high-pressure cryogenic pump-motor system, two kinds of vibration measuring method are used in service. The first method is using the on-line monitoring system that takes the vibration signal from the two radial direction accelerometers installed on submerged pump housing. The other method is using portable vibration measuring equipment

Table 1 Pump specification

Pump Specification	
Capacity (Q)	241.8 m^3/h
Dis' Pressure	88.7 kg/cm^2
Head	1439 m
No. of Impeller	9EA
BRG type	Ball Bearing
No. of Vane	6
Speed	3580 rpm

Table 2 Motor specification

Motor Specification	
Rating	746 kW
Voltage	6600 V
No. of Poles	2
Current	84.5 A
BRG type	6314
No. of Rotor Bar	41

Table 3 Evaluation criteria of vibration (Youn, 1996)

Model	On-Line System	Portable (Local)
Alarm	10∼15 mm/s	1.8∼4.5 mm/s
Trip	Above 15 mm/s	Above 4.5 mm/s

that can take the data at the pump top plate. Table 3 shows the evaluation criteria of high-pressure cryogenic pump vibration, and pump vibration is critically managed to match with the importance of pump in LNG receiving terminal. (Youn, 1996)

3. Vibration and Current Analysis

3.1 Vibration analysis

After the periodic over-haul maintenance, the overall vibration amplitude was increased gradually, and an abnormal periodic noise was generated near the top plate. Figure 3 shows the spectrum data of wide frequency band at the top plate of pump- motor system using the portable vibration measuring equipment. It has been achieved with an accelerometer at radial side, and it was confirmed that the 1X (3,572.6 rpm) frequency peak is 9.175 mm/s.

To confirm a high periodic noise phenomenon

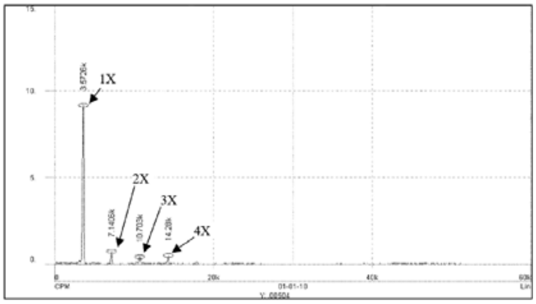

Fig. 3 Spectrum data of top plate (Radial Side)

at local site, the true-zooming spectrum data have been checked at near the 1X frequency as shown in Fig. 4. In the true-zooming spectrum data, multi sidebands near 1X with high peak value are presented, and the interval frequency between 1X and sidebands was about 30 cpm (0.5 Hz). Due to the amplitude and frequency modulation of two near frequency, beat vibration could be verified in true-zooming time waveform in Fig. 4. In Fig. 4, the key area of concern is the presence of so-called pole pass frequency (f_p) as sidebands around motor running speed (1×RPM, f_{shaft}). The pole pass frequency is defined as number of poles (p) times slip frequency (f_{slip}) i.e.,

$$f_{slip}=f_{line}-f_{shaft}=60-59.75=0.25\ \text{Hz} \quad (1)$$

$$f_p=p\times f_{slip}=2\times 0.25=0.5\ \text{Hz} \quad (2)$$

In general, broken rotor bars or end rings will produce pole pass frequency sidebands ($\pm f_p$) around 1×RPM running speed. It often generates sidebands around running speed harmonics (2×, 3×, …). Also, loose or open rotor bars will produce high level of vibrations at Rotor Bar Pass Frequency (RBPF) and/or its harmonics. (Lee, 1998 ; Yang, 1998, 2002 ; Berry, 1994 ; Thomson and Fenger, 2001, 2003) The peak of RBPF in a spectrum appears at a frequency equal to the number of motor bars multiplied by the shaft rate of the machine and will have peaks on either side of it, spaced 120 Hz (7200 rpm) away. These peaks are termed sidebands and they are caused by the modulation of the motor rotor by the electromagnetic forces that cause the motor to spin.

In this paper, the number of motor rotor bar is 41. So RBPF is 41×59.75 Hz=2,450 Hz. The spectrum data of high frequency band has been taken by connecting between on-line monitoring sensor and portable equipment as shown in Fig. 5. In Fig. 5, RBPF component and sidebands of 7,200 rpm interval were generated with high level peaks to compare with 1X, and two and three times RBPF component and side bands interval were also generated with high level amplitude in high frequency band exceptionally.

Through the result of vibration analysis, motor rotor bar or end rings problem is suspected. But it

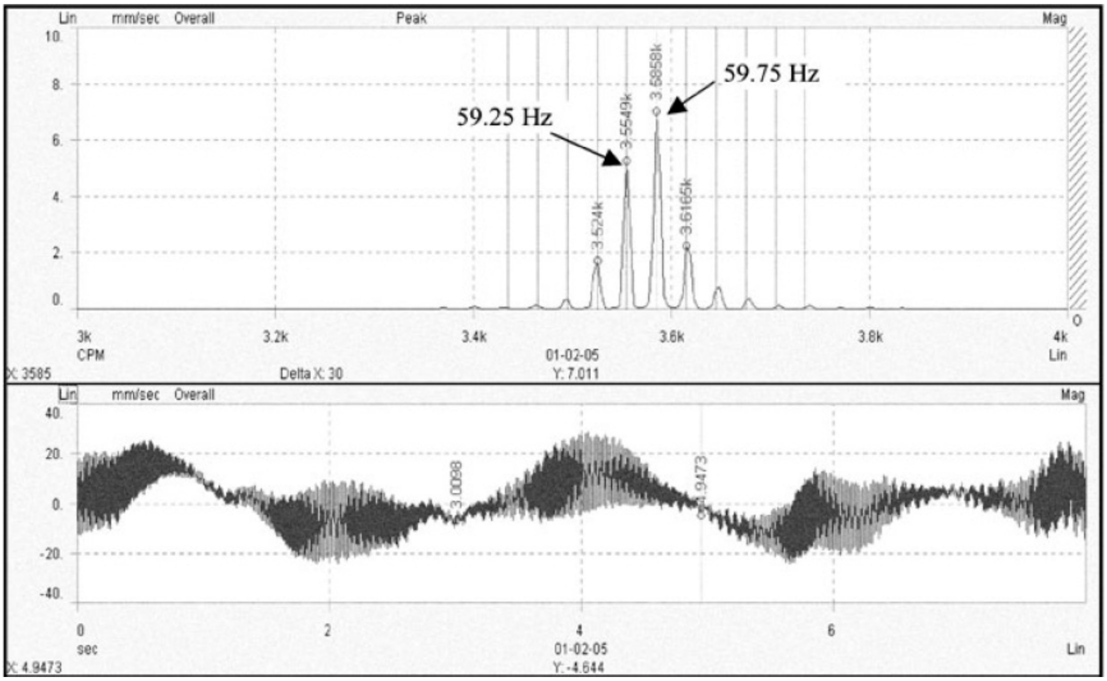

Fig. 4 True-zooming spectrum data and TWF (Top Radial)

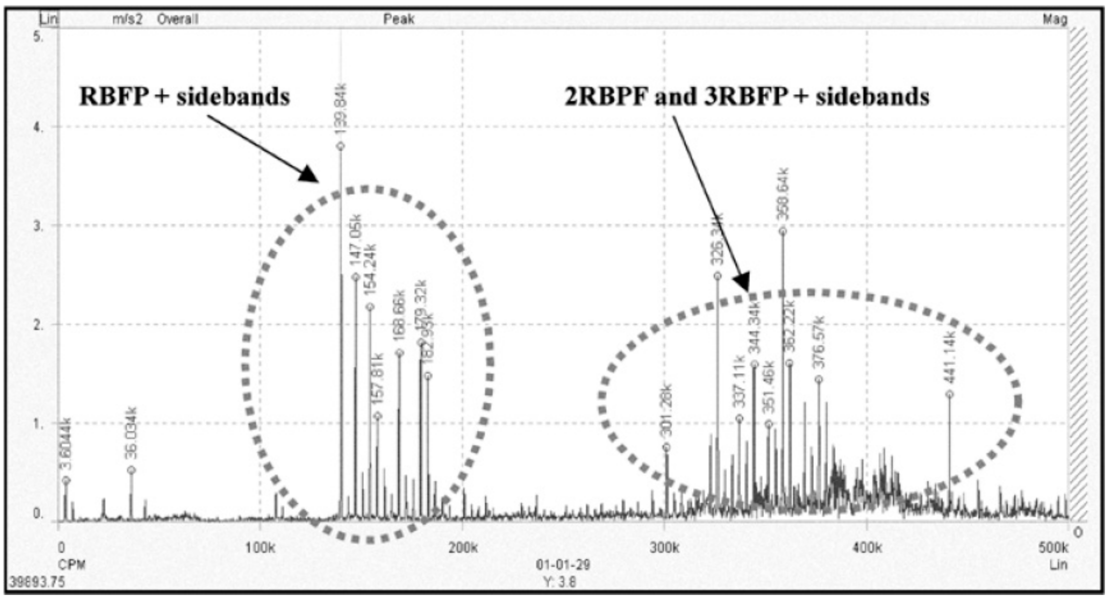

Fig. 5 Vibration spectrum of high frequency band

is very difficult the degree of severity of the rotor bar or end rings fault just only based on the vibration analysis because of the presence of resonances, unbalance and other unknown mechanical influences and conditions. So, to improve the reliability of the vibration diagnosis result, first, rotor influence check was carried out after pump pulled out from vessel for identifying the coherence between phase-to-phase inductance of three phases of motor, and then current signature analysis was also carried out on running state for reconfirming the motor problem and finding the degree of severity of it in this paper.

3.2 Current signature analysis

First, the result of rotor influence check is shown in Fig. 6. As shown in Fig. 6, a little incoherence between phase-to-phase inductance of three phases is appeared. But, in general, the symptoms of crack or short of rotor bar and end-ring could be monitored properly on above the 80% of motor loads. Therefore, current signature analysis was carried out on running state. There are two types of circuits for induction motors, namely main phase circuit and secondary circuit. The preferred method for motor current measurement is to clamp the current transformer onto the secondary circuit for the motor. This is a low amperage circuit and is easily accessed in the switch gear cabinet for the induction motor as shown in Fig. 7.

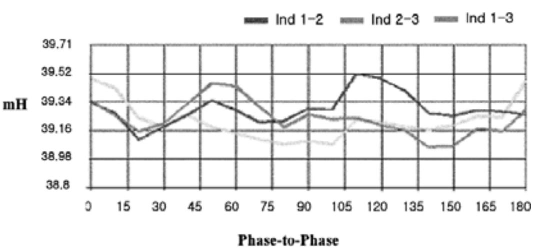

Fig. 6 Result of rotor influence check

Fig. 7 Current analysis of running motor

The presence of a defective rotor bar will cause the motor torque to be reduced slightly every time a pole of the rotating magnetic field passes by it. This happens at twice the slip frequency, for both the north and south poles of the field cause a momentary reduction. Thus rotor bar problem has been shown to produce sidebands around the fundamental supply frequency f_{line} at $(1\pm2\,S)f_{line}$ in current spectrum. Therefore, in motor current analysis, the sidebands $(1\pm2\,S)f_{line}$ around line frequency are major concerns for broken rotor bars and the key step is to accurately identify the line frequency and two sidebands. The motor torque reduction caused by the fractures in the rotor bars or end ring also results in a reduction in the input current to the motor at the same rate. This periodic reduction in the motor current is actually an amplitude and phase angle modulation of the motor current. The relative amplitudes of these sidebands to the line frequency component from the basis for the prediction of rotor circuit health, namely, the amount of modulation is related to the severity of the rotor bar problem. (Thomson and Fenger, 2001, 2003)

From the definitions of synchronous frequency (f_{sync}) and the slip ratio (S) as in Eq. (3) and Eq. (4), the relationship between the sidebands $(1\pm2\,S)f_{line}$ in a current spectrum and pole pass frequency sidebands ($\pm f_p$) can be derived as follows :

$$f_{sync}=2\times f_{line}/P=60\text{ Hz} \quad (3)$$

$$S=\frac{f_{slip}}{f_{sync}}=\frac{P\times f_{slip}}{2\times f_{line}}=\frac{0.25}{60}\times 0.004167 \quad (4)$$

Thus,

$$2S\times f_{line}=P\times f_{slip}=f_p=2\times 0.004167\times 60=0.5\text{ Hz}$$

$$(1\pm 2S)f_{line}=60\pm 0.5\text{ Hz (59.5 Hz and 60.5 Hz)}$$

Therefore, the sidebands in both current spectrum and vibration spectrum have the same spacing from the carrier frequency. The only differences is that the carrier frequency in a vibration spectrum.

The result of current signature analysis was shown in the Fig. 8. In Fig. 8, it could be confirmed that the amplitudes gap of between sidebands (59.5 Hz and 60.5 Hz) and line frequency (60 Hz) was from 36 dB to 39 dB in current spectrum. Generally this amplitude gap indicates that one or two rotor bars were cracked or broken according to the rotor bar damage severity level chart as shown in Table 4.(Bonnet and Soukup, 1992 ; Berry. and James, 1999 ; Finley et al., 2000 ; Thomson and Fenger, 2001, 2003)

With the above result of current analysis, motor rotor bar problem was confirmed again, therefore, motor was removed from service and repaired for the modification of abnormal vibration cause.

After pulled out and disassembly of pump-motor system, there was a crack and rubbing mark in the pump shaft because of the excessive vibration of pump and the bushing which contacts with pump shaft in diffuser housing was excessively worn as shown in Figs. 9 and 10 respectively.

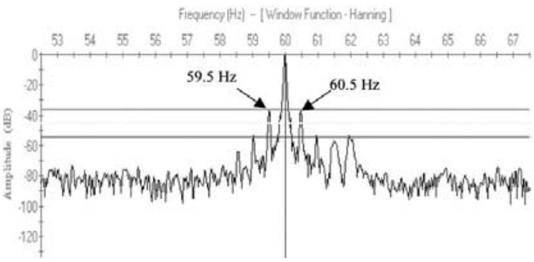

Fig. 8 High resolution spectrum of current signal

Fig. 9 Crack and rubbing mark in pump shaft

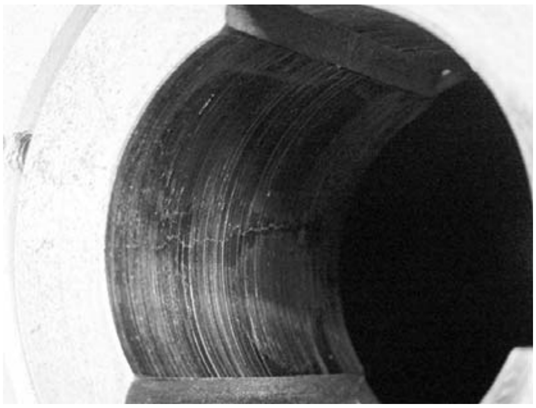

Fig. 10 Excessive wear of pump shaft bushing

Table 4 Rotor bar damage severity level chart

Rotor bar damage severity level chart					
Severity Level	f_{line}/f_p (dB)	f_{line}/f_p (Ratio)	f_{line}/f_p (Ratio %)	Condition Assessment	Recommended action
1	>60	>1000	>0.10	Excellent	None
2	54~60	501~1000	0.01~0.2	Good	None
3	48~54	251~501	0.2~0.4	Moderate	Trend data
4	42~48	126~251	0.4~0.79	Rotor bar crack may be developing problems with high resistance	Increasing trending frequency
5	**36~42**	63~126	0.79~1.58	**One or two rotor bars cracked or broken**	Perform vibration test to confirm source
6	30~36	32~63	1.58~3.16	Multiple cracked or broken rotor bars	Repair ASAP
7	<30	<32	>3.12	Multiple cracked or broken rotor bars	Repair or replace ASAP

Fig. 11 Suspected cracked or broken area between botor bar and end-ring

Also, a suspected cracked or broken area between rotor bar and end-ring was checked visually as shown in the Fig. 11.

4. Modification of Vibration Cause

4.1 Repairing of rotor

Based on the measured the vibration and current analysis data, motor was repaired to solve the vibration problem that is originated from the short of rotor bar and end-ring. The material of rotor bar and end-ring in high-pressure cryogenic pumps are consisting of Al alloy, but it was difficult to repair those with same material technically. Therefore, it was repaired with changing by Cu alloy instead of Al alloy after mechanical test in super cooled temperature. Figure 12 is shown the removed state of rotor bar and end-ring in rotor. Also, visual check and weight balancing as shown in Table 5 was carried out again after motor repairing.

4.2 Comparison of vibration characteristic after repairing

In Fig. 13, the overall vibration values are reduced after repairing. And it could be verified the amplitude peak of rotating frequency component (1X) was significantly reduced with about 1.5 mm/s, e.g., approximately 80% level of vibration than before repairing.

After repairing, as result with the checking spectrum of high frequency band, RBPF component

Table 5 Weight balancing data

ISO 1940/1 Grade G2.5	Before balancing		After balancing	
	Plane 1	Plane 2	Plane 1	Plane 2
Unbalance (gr.)	85.96	74.49	0.79	0.99
Degree	55.1	27.4	122.8	257.1

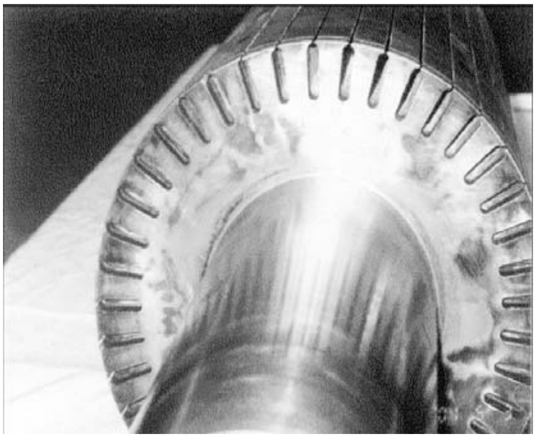

Fig. 12 Remove state of rotor bars and end-ring

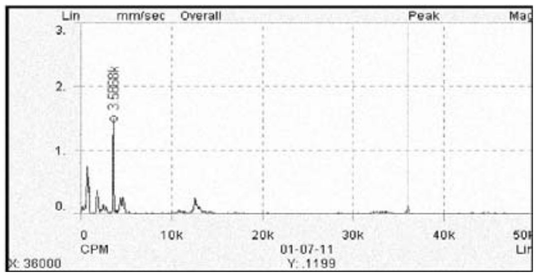

Fig. 13 Vibration spectrum of low frequency band after repairing

and sideband components are generated as same as before repair. However, it was verified that two and three times RBPF and side band components are almost disappeared and the amplitude is significantly reduced as shown in Fig. 14.

In zooming spectrum near the 1X which is shown in Fig. 15, multiple sideband components with interval frequency (0.5 Hz) with 1X originated from pole pass frequency (f_P) are disappeared, and sideband components which have small peak value with about 0.33 Hz interval are observed only. In addition, it could be verified that amplitude of 1X component is significantly reduced and periodical beat vibration on the time waveform data is disappeared and random low-frequency wave is just observed.

In Fig. 16, the current spectrum of motor after repairing is shown. As can be seen from Fig. 16, the spectrum is completely free of any current components around the line frequency (60 Hz) and consequently, the frequency range (59.5 Hz and 60.5 Hz) in which the current components

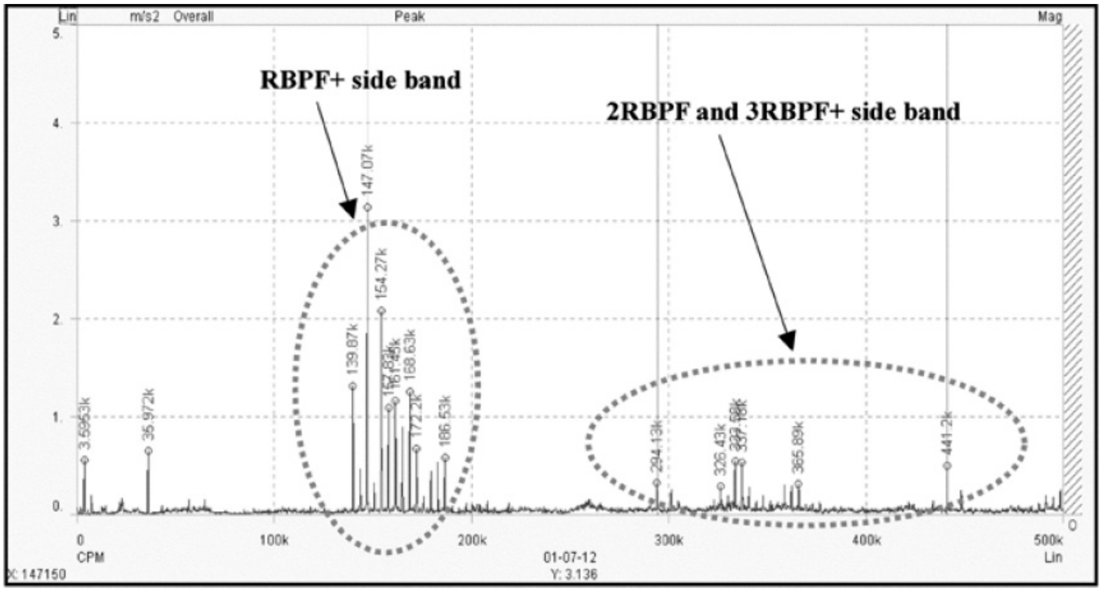

Fig. 14 Spectrum of high frequency band after repairing

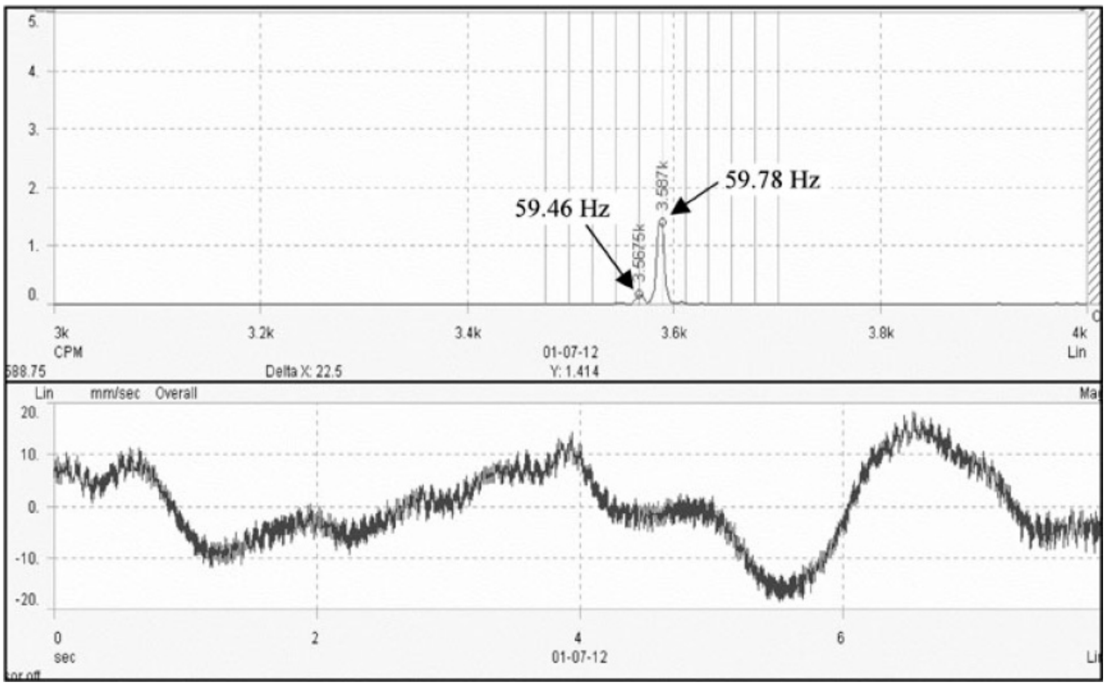

Fig. 15 True-zooming spectrum data and TWF (Top Radial)

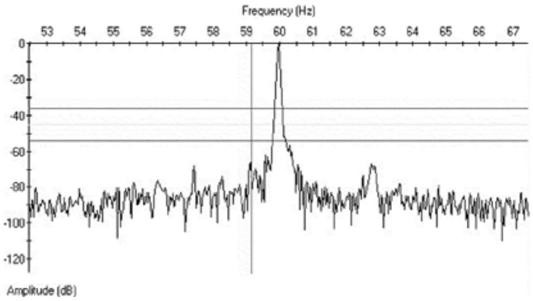

Fig. 16 High resolution spectrum of current signal (after repairing)

due to broken rotor bars are expected are empty. The motor thus show no signs of broken rotor bar.

5. Conclusions

In this paper, through the vibration diagnosis of the high-pressure cryogenic pump-motor system that is operated on super-low temperature (−162℃), firstly electrical problem is confirmed by vibration analysis. And then, to improve the reliability of the vibration diagnosis result, current signature analysis carried out on motor running state together. That was allowed to figure out the exact causes of abnormal vibration problem of cryogenic pump-motor system, to repair properly the broken rotor bars and end-ring.

Although motor rotor was repaired with alternated material, the performance of modified rotor could be identified appropriately by the comparison of vibration and current characteristics before and after repairing.

In this case of view, the diagnosis efficiency of condition monitoring of cryogenic pump-motor system could be raised more by using both analysis, namely the vibration and the current signature analysis, for early and exact detection of the abnormal conditions.

Acknowledgments

This study is supported by Second-Phase of Brain Korea 21 Project and New University for Regional Innovation (NURI) Project.

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