Separation of Noise and Signals by Independent Component Analysis

Sigeru Omatu, Masao Fujimura, Toshihisa Kosaka
Osaka Institute of Tecnology, *Glory Ltd*
Asahi-ku, Osaka, 535-8585, Osaka, Japan, *Himeji, Hyogo, Japan*
{*omatu@rsh., Fujimura@elc.*}*oit.ac.jp,* *kosaka@tec.glory.co.jp*

***Abstract*—A separation problem of acoustic signals and noise by using the independent component analysis (ICA) with band-pass filters is proposed. The frequency distribution of a recorded acoustic signal of the operating mechanical device can be divided into three fields, the low-frequency field, which corresponds to the frequency characteristics of the gear, the medium-frequency field, which is mixed with the frequency characteristics of the gear and the motor, and the high-frequency field, which corresponds to the frequency characteristics of the motor. Since only the medium-frequency components are the mixture of acoustic signals of gears and motors, the ICA with band-pass filters is expected to separate the acoustic signals of motors and gears more accurately than the conventional ICA. The simulation and experimental results show that the proposed method can separate the acoustic signals of motors and gears of mechanical devices successfully.**

***Keywords*-signal separation, independent component analysis, neural networks**

I. Introduction

In the quality evaluation of mechanical devices, it is important to separate the acoustic signals of motors and gears in order to identify the causes of failures. The ICA method, which is developed to solve the cocktail-party problem, can separate two independent acoustic signals from their mixtures by using the information measure of statistically independent properties [1],[2], and [3]. However, many applications in practice denote that the ICA does not perform well in separation by using the observed acoustic signals directly [4]-[5]. In order to separate the independent acoustic signals correctly, additional data processing is necessary before applying the ICA. By applying the fast Fourier transform (FFT) to a recorded acoustic signal of the operating mechanical device, we observe that its frequency distribution can be divided into three fields, the low-frequency field, which corresponds to the frequency characteristics of the gear, the medium-frequency field, which is mixed with the frequency characteristics of the gear and the motor, and the high-frequency field, which corresponds to the frequency characteristics of the motor. Since the frequencies of a motor may be harmonics of the fundamental frequencies of a gear, which causes the independence assumption of the sources to fail and affects the separation accuracy. Therefore, the mixed acoustic signals with less frequency components are expected to be separated more accurately. In this paper, the ICA with band-pass filters is used to separate the acoustic signals of gears and motors. We first record the acoustic signals of the operating mechanical devices. By applying the band-pass filters, the respective components of low- frequency, medium-frequency and high-frequency can be obtained. Then the medium-frequency components are given to the ICA. After separation, the acoustic signals of gears and motors are recovered by adding the low-frequency and high-frequency components to the separated results, respectively. In this paper, the mixtures of two independent signals are also designed to simulate the separation process of acoustic signals of a gear and a motor. Both the simulation results and the experimental results show that the better separation results can be obtained by using the mixed medium-frequency field than using the whole frequency field.

II. Principle of ICA

Let us summarize the principle of the ICA and state some problem when we use the ICA directly. For simplicity, we assume two source signals denoted by s_1 and s_1 which are statistically independent each other. Furthermore, we assume that those signals are observed by two microphones and denoted by x_1 and x_2. The relation is given by the following equations:

$$x_1 = a_{11}s_1 + a_{12}s_2x_2 = a_{21}s_1 + a_{22}s_2 \tag{1}$$

where $a_{ij}, i, j = 1, 2$ are unknown constant. Using the vector notation, we have

$$x = As, \quad x = (y_1, y_2)^t, s = (s_1, s_2)^t \tag{2}$$

where an unknown matrix A is given by

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}.$$

From the observed vector x, we estimate the original signal vector s by the following linear transform

$$\hat{s} = wx \tag{3}$$

where

$$w = \begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix}$$

such that the following J can be minimized

$$J = \int p(\hat{s}) log \frac{p(\hat{s})}{p(\hat{s_1})p(\hat{s_2})} d\hat{s}. \tag{4}$$

There are some algorithms to minimize J, we adopt the fast ICA developed by Hyvarinen A. *et al* [1]

 ISBN: 978-1-61208-101-4

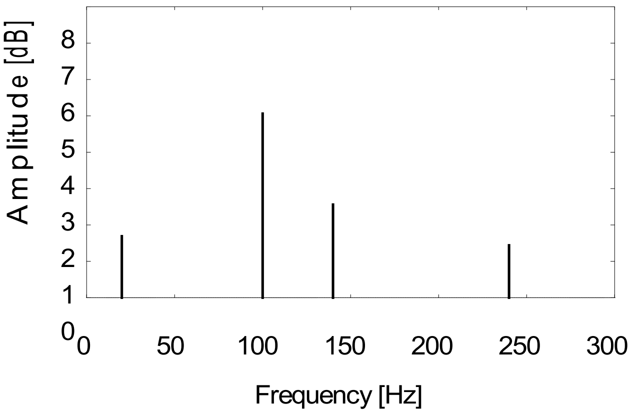

Fig. 1. Frequency characteristic of $x_1(t)$.

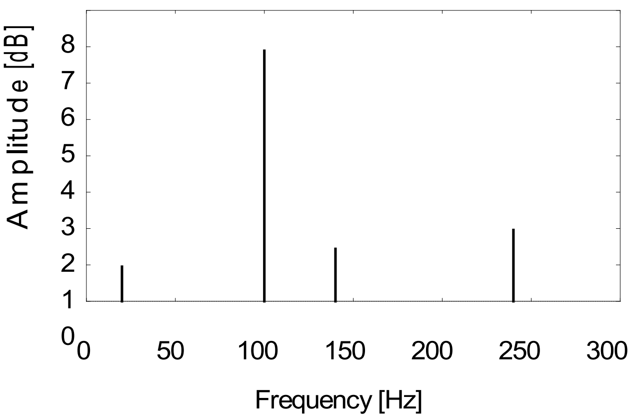

Fig. 2. Frequency characteristic of $x_2(t)$.

III. SIMULATION RESULTS

We have tried the signal separation using the fast ICA algorithm in case of $f_1 = 20$Hz,$f_2 = 140$Hz,$f_3 = 100$Hz, and $f_4 = 240$Hz and $a_{11} = 2, a_{12} = 1.2, a_{21} = 1$, and $a_{22} = 1.3$. The spectra of two independent signals $x_1(t)$ and $x_2(t)$ are illustrated in Figs. 1 and 2, respectively. The corresponding spectra of recovered signals are illustrated in Figs. 3 and 4.

From these results, signal separations for these data are not good since frequencies except for the original signals are remained.

However, if we select several frequencies, some combinations of them could recover the original signals perfectly. To see this effect, we have tried the following simulation in case where f_1, f_2 and f_4 are fixed and f_3 is changed.

If we use two microphones to record the acoustic signals, we have two observed signals given by

$$x_1(t) = a_{11}s_1(t) + a_{12}s_2(t)$$
$$x_2(t) = a_{21}s_1(t) + a_{22}s_2(t).$$

We use the ICA to separate the two independent acoustic signals $s_1(t)$ and $s_2(t)$ from the observed signals $x_1(t)$ and $x_2(t)$. Table I shows the separation results where "Y" denotes that the independent signals $s_1(t)$ and $s_2(t)$ can be separated correctly and "N" denotes that they cannot be separated

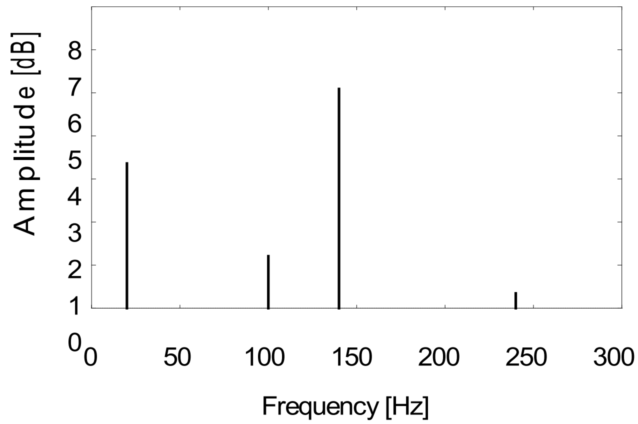

Fig. 3. Frequency characteristic of $\hat{s}_1(t)$.

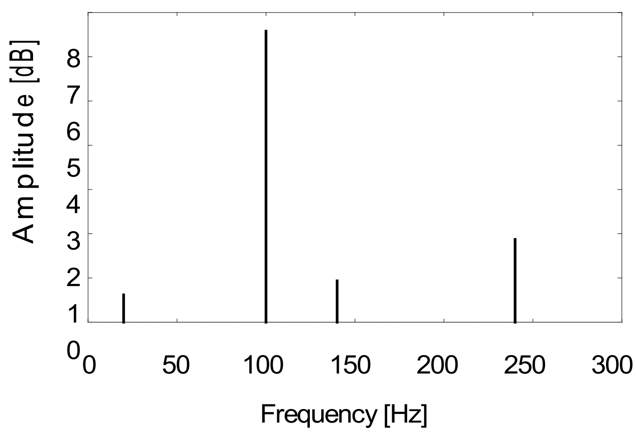

Fig. 4. Frequency characteristic of $\hat{s}_2(t)$.

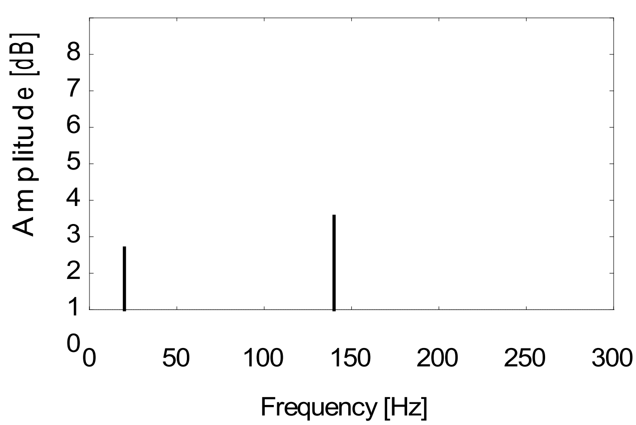

Fig. 5. Frequency characteristic of s_1.

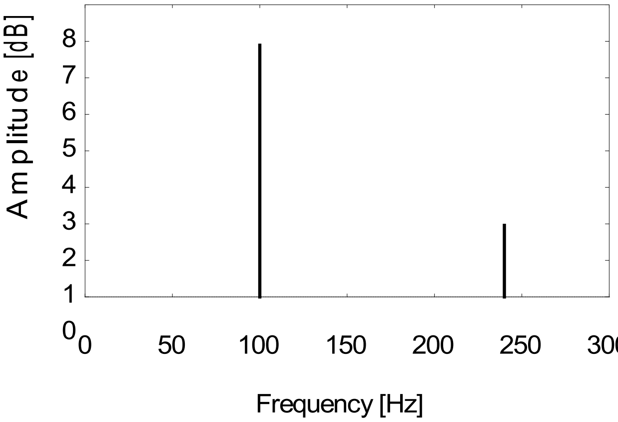

Fig. 6. Frequency characteristic of s_2.

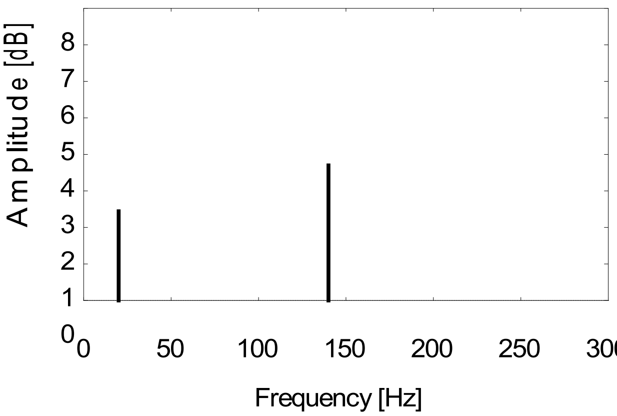

Fig. 7. Frequency characteristic of separated signal $\hat{s}_1(t)$ with band-pass filters.

correctly. From Table I, it can be seen that sometimes we fail in separating the acoustic signals $s_1(t)$ and $s_2(t)$ by using the observed signals $x_1(t)$ and $x_2(t)$ directly.

However, after filtering the frequency components f_1 and f_4 with a band-pass filter, the frequency components f_2 and f_3 can be separated successfully by using the ICA. Thus, the original acoustic signals $s_1(t)$ and $s_2(t)$ can be obtained by adding the frequency components f_1 and f_4 to the separation results of the ICA, respectively. As an example, Figs. 7 and 8 show the frequency characteristics of separated signals $\hat{s}_1(t)$ and $\hat{s}_2(t)$ by using the ICA with band-pass filters, respectively where $f_1 = 100$Hz. From these figures, it can be seen that the two acoustic signals of $s_1(t)$ and $s_2(t)$ are recovered correctly.

Similarly, other unsuccessful separation experiments of Table I are redone by using the ICA with band-pass filters. The simulation results show that all the signals are separated successfully. And the separation experiments of mixed acoustic signals with multi-frequencies also show that the ICA with band-pass filters performs better than the conventional ICA in acoustic signals separation.

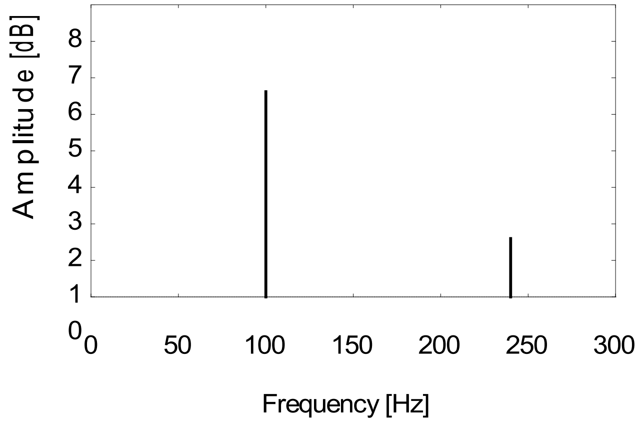

Fig. 8. Frequency characteristic of separated signal $\hat{s}_2(t)$ with band-pass filters.

TABLE I
SEPARATION RESULTS OF OBSERVED SIGNALS (UNIT: HZ) WHERE $f_1 = 20, f_2 = 140, f_4 = 240$.

f_3	30	40	50	60	70	80
Y or N	Y	Y	Y	N	Y	Y
f_3	90	100	110	120	130	150
Y or N	Y	N	Y	N	Y	Y
f_3	160	170	180	190	210	230
Y or N	Y	Y	N	Y	Y	Y

IV. EXPERIMENTAL RESULTS

According to the above simulation results, we separate the acoustic signals of motors and gears of mechanical devices by using the ICA with band-pass filters. The acoustic signals recording system is shown in Fig.5. Two microphones, which are held in different locations, are used to record the acoustic signals of operating mechanical devices. By applying the band-pass filters, we obtain the respective components of low-frequency, medium-frequency and high-frequency. Since only the medium-frequency components are the mixture of acoustic signals of gears and motors, we input the medium-frequency components to the ICA. Then the acoustic signals of gears and motors can be recovered by adding the low-frequency and high-frequency components to the separation results of the ICA, respectively.

An example of acoustic signals recorded by microphones L and R are shown in Figs. 10 and 11, respectively where the sampling rate is 8,000. Their frequency characteristics are shown in Figs. 12 and 13. Since the rotational speed of the motor is 3600 rpm and the rotor has 12 poles, the fundamental frequency of the motor is about 360 Hz. Similarly, since the gear ratio is 30:1, the fundamental frequency of the gear is about 12 Hz. Thus, it can be considered that the medium-frequency is the range of 300 to 2,000 Hz and the relevant band-pass filters are designed.

In Figs. 14 and 15, the medium-frequency fields of acoustic signals of left and right microphones with the band-pass filter are given respectively. The filtered signals are used as the input of the ICA. The spectra of the separated acoustic signals are

 ISBN: 978-1-61208-101-4

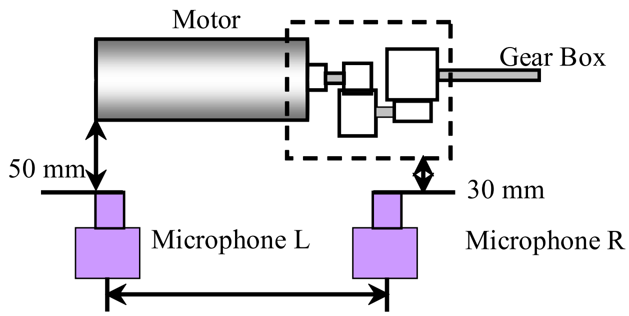

Fig. 9. The acoustic signals recording system.

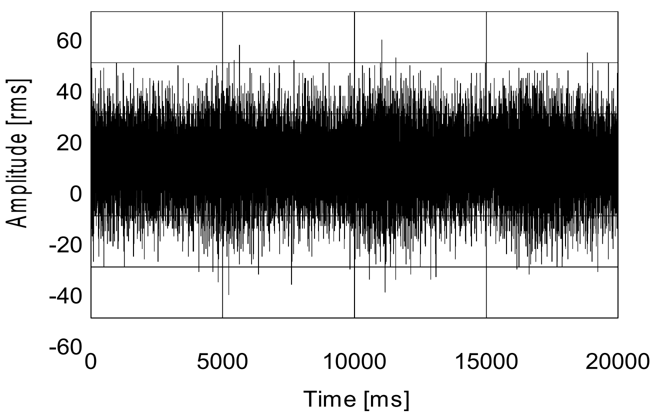

Fig. 10. Acoustic signal recorded by the left microphone.

shown in Figs. 16 and 17. Since a peak of amplitude nearby 1,000 Hz, which is about 3 times of the fundamental frequency of the motor, can be observed in Fig. 12, it is regarded that Figs. 16 and 17 show the medium-frequency fields of acoustic signals of the motor and the gear, respectively.

To verify the effectiveness of our proposed method, we also give the separation results by applying the recorded acoustic signals of mechanical devices to the ICA directly.

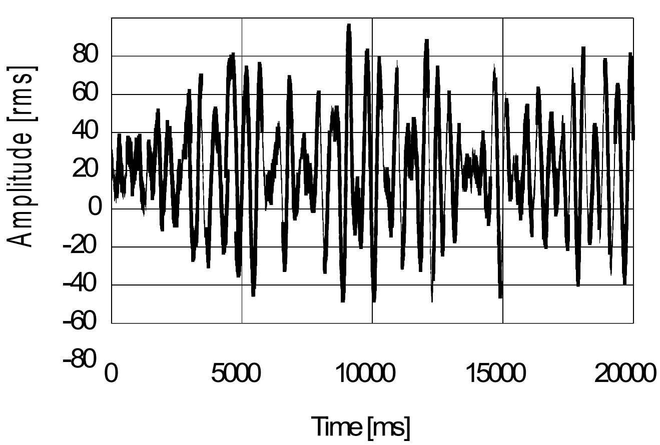

Fig. 11. Acoustic signal recorded by the right microphone.

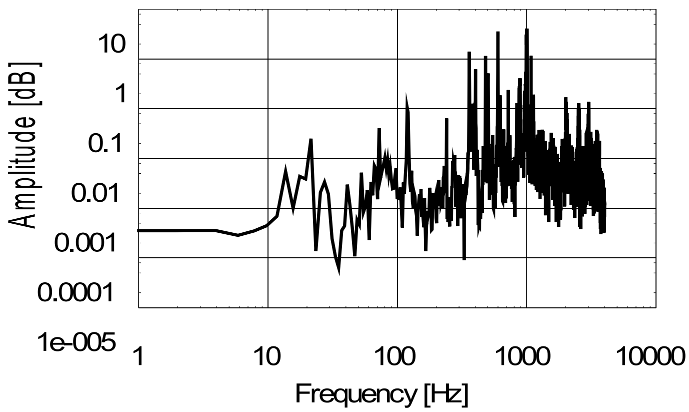

Fig. 12. Spectrum of acoustic signal of left microphone.

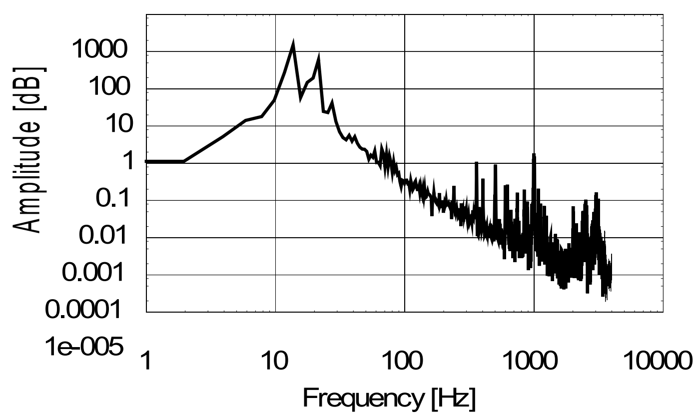

Fig. 13. Spectrum of acoustic signal of right microphone.

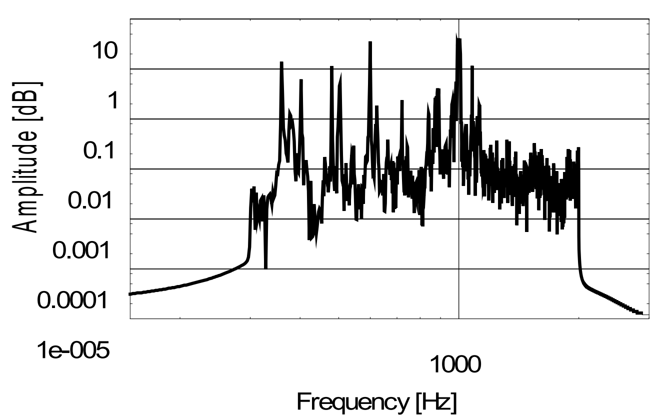

Fig. 14. Spectrum of Fig. 8 with a band-pass filter.

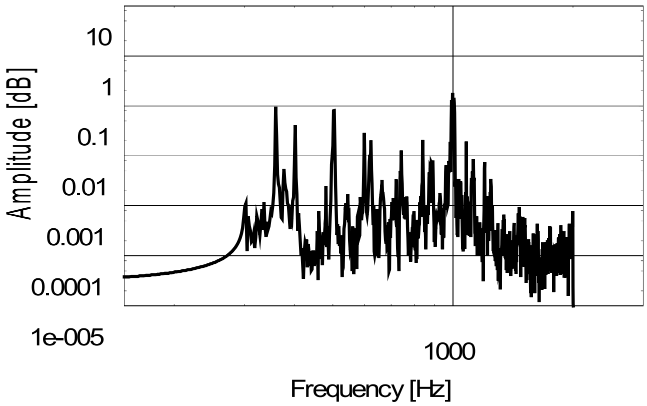

Fig. 15. Spectrum of Fig. 13 with a band-pass filter.

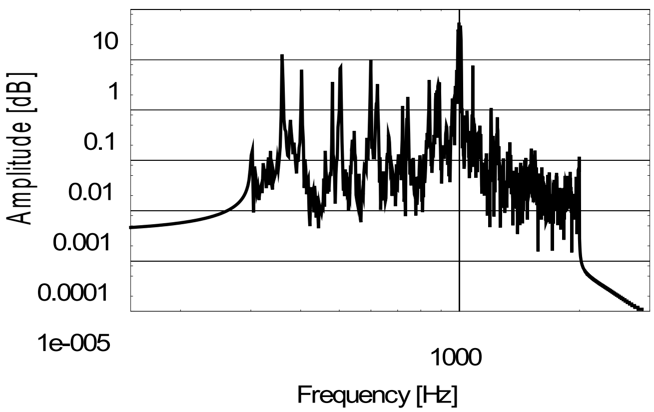

Fig. 16. Spectrum of the separated acoustic signal by using the ICA with a band-pass filter (motor).

The frequency characteristics of the separated acoustic signal are shown in Figs. 18 and 20, and the medium-frequency characteristics are shown in Figs. 19 and 21. Comparing with Figs. 12 and 13, it can be concluded that Figs. 18-20 show the frequency characteristics of the motor and the gear, respectively.

From the above figures, it can be seen that the ICA with band-pass filters performs better than the conventional ICA in acoustic signals separation. The spectrum of Fig. 19 is similar with the one of Fig. 21, especially the peaks of amplitudes appeared in both figures, which are located in the multiple of fundamental frequency of the motor, denote that the separation results of acoustic signals of the motor and the gear are not good.

The acoustic signals of the gear and the motor are recovered by adding the low-frequency and high- frequency components to the separation results of Figs. 16 and 17, respectively. The spectra of recovered acoustic signals of the gear and the motor are shown in Figs. 22 and 23 where the amplitudes of medium-frequency are adjusted according to the amplitudes of low-frequency and high-frequency, respectively. Comparing with the above figures, it can be concluded that the separation results are reasonable. The separated acoustic signals of the

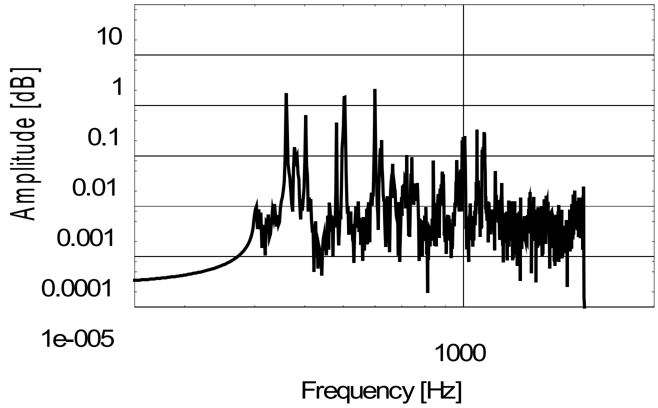

Fig. 17. Spectrum of the separated acoustic signal by using the ICA with a band filter-pass (gear).

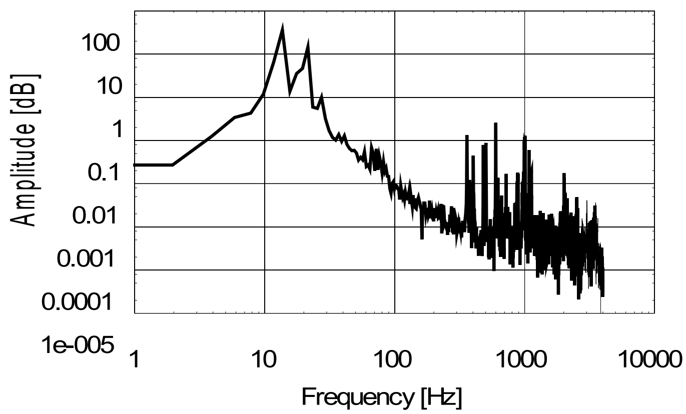

Fig. 18. Frequency characteristics of the separated acoustic signal by using the ICA (motor).

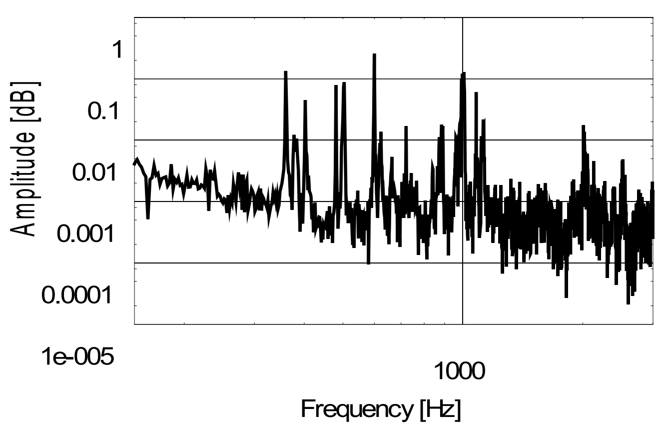

Fig. 19. Medium-frequency characteristics of the separated acoustic signal by using the ICA (motor).

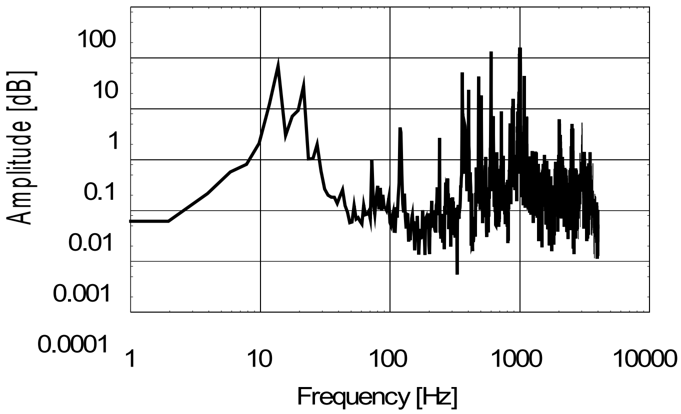

Fig. 20. Frequency characteristics of the separated acoustic signal by using the ICA (gear).

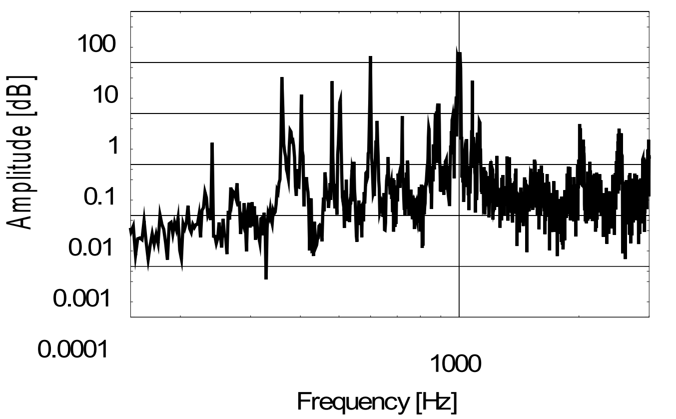

Fig. 21. Medium-frequency characteristics of the separated acoustic signal by using the ICA (gear).

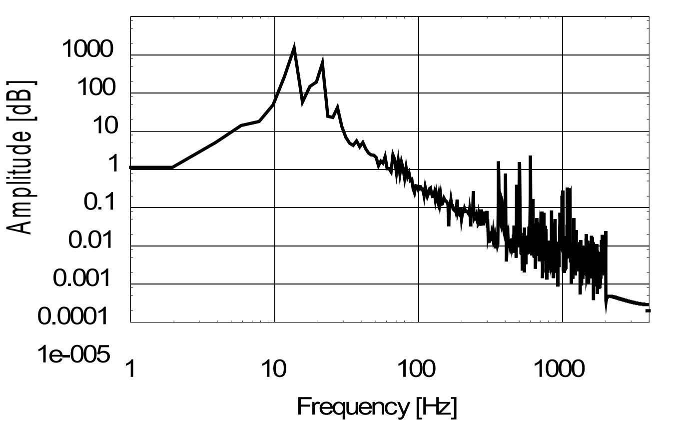

Fig. 22. Spectrum of recovered acoustic signal of the gear.

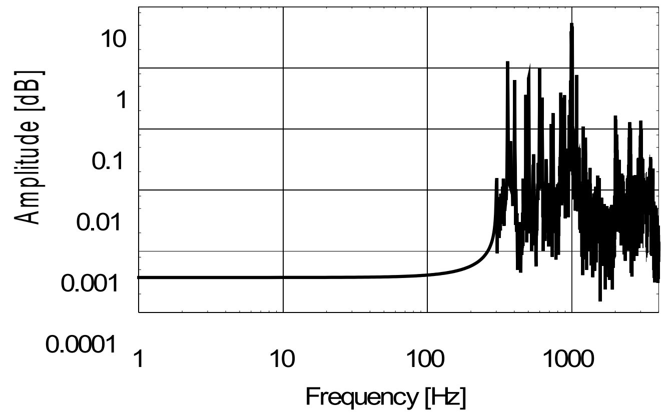

Fig. 23. Spectrum of recovered acoustic signal of the motor.

gear and the motor are also checked by a technician, the sounds of the motor and the gear denote that the acoustic signals of the gear and the motor are separated successfully by using the ICA with band-pass filters.

V. CONCLUSIONS

In this paper, a method of separating the acoustic signals of gears and motors of mechanical devices by using the ICA with band-pass filter is proposed. The simulation results denote that the mixed acoustic signals with less frequency components can achieve better separation performance by using the ICA. Therefore, for those independent signals which are mixed only in medium-frequency field, the ICA with band-pass filters can separate the independent original signals more accurately than the conventional ICA. Using the proposed method, we have solved the acoustic signals separation problem of gears and motors of mechanical devices successfully.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (B) (20360178). The authors would like to thank JSPS to support this research work.

REFERENCES

[1] Hyvarinen A. , Karhumen J. , and Oja E. , Independent Component Analysis, Wiley Publisher, New York, (2001)
[2] Bingham E. , and Hyvarinen A. , A fast fixed-point algorithm for independent component analysis of complex valued signals, International Journal of Neural Systems, 10–1, 1–8 (2000)
[3] Hochreiter S. , and Schmidhuber J. , LOCOCODE performs nonlinear ICA without knowing the number of sources, Proceedings of the First International Workshop on ICA and Signal Separation, Aussois, France, 149–154 (1999)
[4] Lee T. W. , *Independent Component Analysis: Theory and Applications*, Kluwer Academic Publishers, Boston (1998)
[5] Cichocki A. , and Amari S. , *Adaptive Blind Signal and Image Processing: Learning Alogarithms and Applications*, Wiley Publisher, New York (2002)

 ISBN: 978-1-61208-101-4