Development of a procedure to detect quantified abnormal noise

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Abstract

As automobile passenger rooms have become quieter in recent years, silencing and the quality of operational noise from audio and navigation products are becoming more crucial. It is now important to improve the quality of operational noise as well as to detect abnormal operational noise. Up to the present, operational noise inspection was performed at our company by human ear. However, an application of a strict inspection standard is required now that passenger rooms are much quieter, and it is becoming more difficult to secure an adequate inspection quality by relying on human ears alone. In order to quantitatively inspect abnormalities in operational noise, typical noise gauges and frequency analysis methods were evaluated, but a satisfactory inspection precision could not be gained.

We have finally developed a method to quantify characteristics of operational noise and to judge these quantitatively, and have completed an automatic noise inspection equipment. This new technology is described hereafter.

1 Introduction

When a machine operates, it generally emits operational sound. If any abnormality occurs in the parts or in the assembly process, such sound often turns into abnormal sound (hereafter, abnormal noise). In such events, it has been an ordinary case to rely on workers' sensation when selecting the means to determine whether the noise is normal or not, so far. However, we could not define a quantitative threshold value because of variation due to workers' physical or other conditions and their own standard differences for judgment. To avoid such variation, we set a boundary sample as an abnormal noise sample, but there was an issue that the sound of that sample might change in several years after setting, causing the criteria to shift, and it was necessary to periodically check the boundary sample.

In recent years, it is more silent than before inside automobile passenger rooms, and customers' quality demand for operational noise is becoming more stringent. Because of this, it is necessary to evaluate sound to a constant standard to supply products of stable operational sound quality. If a work (in-process product) that emits abnormal noise and enters subsequent processes, confusion arises there. Releasing such products may eventually lower the level of customer satisfaction, and thus it is very important to prevent abnormal noise from arising or to prevent such products from entering subsequent processes.

This paper reports our developed technique that can quantify and evaluate abnormal noise, which was conventionally relied on human audibility, from the viewpoint of prevention of abnormal noise occurrence and outflow of these defects, as well as the functions and features of the method.

2 Target of development and conventional technology

2.1 Subject of development

For the subject of this development, we selected search sound emitted from the pickup (hereafter, PU) of the drive unit (hereafter, DU) mounted in CD changers manufactured by Fujitsu Ten (see Figure 1).

When the gear train rotates and the PU moves in horizontal direction, the unit emits a search sound. When the DU is completed, it is assembled in the deck, and when the deck is completed, it is assembled in the product as defined in the in-house process flow. The reason why we selected this sound is because abnormal noise was detected mainly in the subsequent processes rather than in the DU process although inspection of abnormal noise was performed in the DU assembly process, as shown in Figure 2.

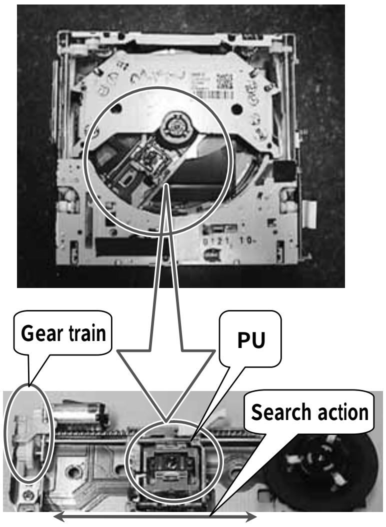


Fig.1 CD changer and DU

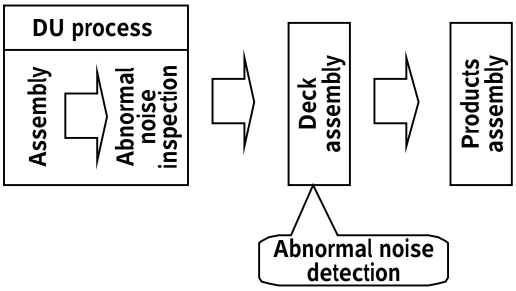


Fig.2 Abnormal noise detection timing

The cause why abnormal sound could not be detected in the DU process was that it was hard to distinguish abnormal noise from other sounds in the state of DU because the sound was differently heard from in the state of being mounted in a product. Therefore, we considered that the detecting ability was insufficient by the current method of abnormal noise inspection with human audibility, and we decided to develop a new inspection method that would allow quantitative evaluation. If we could detect abnormal noise in the DU assembly process and prevent abnormal noise from outflowing, or more particularly, prevent the noise-emitting DU from going to subsequent processes, we would be able to clarify the cause then and there, improving the noise prevention activity.

2.2 Target of development

To start the development, we set the following targets:

①ZERO outflow of abnormal noise

Detect all abnormal noise, preventing defective DUs from going to the subsequent process.

②Setting an over-detection target

Avoid wrong judgment taking a defective item for a conforming item when quantitatively evaluating sounds or noises. To do this, it is necessary to set a rather strict inspection rule to "Take a doubtful sound as nonconformity", which we call over-detection. If this rule is set to a too stringent level, it will result in a too low run-through rate of the inspection process. Therefore, we set a target that the level of over-detection will be equal to or less than the current number of outflow to subsequent processes.

2.3 Mechanism of abnormal noise emission

When a PU is in a search action, the gear is rotating. If any abnormality occurs here in this revolving system, the gears will run out of normal engagement. This is the mechanism to emit abnormal noise. More specifically, major causes include gear flaws, mixing of foreign objects and other abnormality in parts of the traveling system, as shown in Figure 3. Since the gears are rotating at a high speed, even a microscopic abnormality may cause abnormal noise due to poor gear engagement.

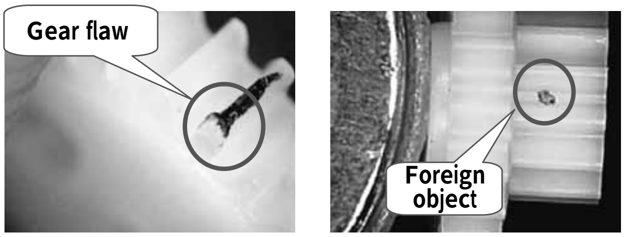


Fig.3 Gear abnormality

Abnormal noise can be essentially divided into two types in terms of audibility trend.

①Magnified sound of whole operational noise (hereafter, gear sound)

②Sound containing periodic noise (hereafter, rattling sound)

2.4 Conventional technology

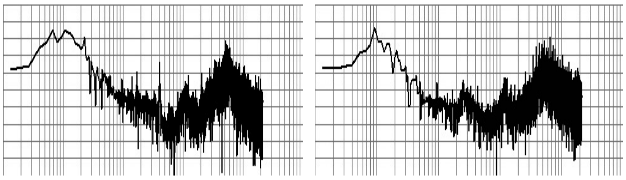
To measure sounds, we generally have some methods such as noise gauge and FFT. However, those methods involve such defects as listed in Table 1 when evaluating abnormal noise, and therefore, we could not perform satisfactory detection with those methods.

Table 1 Conventional measurement methods

	Advantage	Disadvantage
Noise gauge	Easy to measure	Noise can be evaluated only by the magnitude of sound pressure as shown in Figure 4 (abnormal noise does not always have a high sound pressure).
Frequency analysis (FFT)	We can easily identify the band to which the strong components belong because analysis can be made in each small frequency band.	Since the noise is leveled by time-averaging process, resulting in a waveform as shown in Figure 5, we cannot positively identify it as abnormal noise.

Normal noise　Abnormal noise

Fig.4 Comparison by noise gauge



Normal noise　Abnormal noise

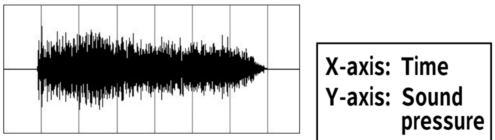
Fig.5 Comparison by FFT

Thus, it is important to establish a new method of measurement and analysis that can distinguish between normal noise and abnormal noise.

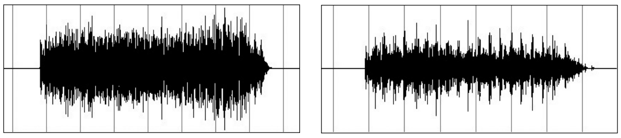
3 Sound analysis and development of unique algorithm

3.1 Difference between normal noise and abnormal noise

Comparison of waveform recorded by microphone between normal and abnormal noise is shown in Figure 6. The gear sound has a waveform of high level on the whole, and the rattling sound has a waveform of low level, involving periodic peaks or projections. However, the normal noise does not always have a constant level, either, and therefore, it is difficult to identify abnormal noise only by glancing the raw waveform.



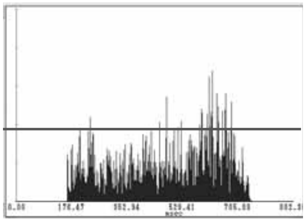
Normal noise



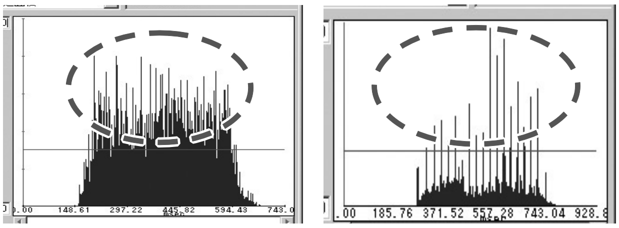
Gear sound　Rattling sound

Fig.6 Normal noise and abnormal noise waves

Now, in order to emphasize the difference of waveform between normal noise and abnormal noise, we put the raw waveform in a root-mean-square process. And that, we first emphasized the band of 3 to 4 kHz, in which the sensitivity of human auditory sense is high, as generally said, and then the result was subjected to root-mean-square processing, and we examined whether it is possible or not to detect abnormal noise. Figure 7 shows the waveforms after going through the processing. Compared to the raw waveforms, we can see conspicuous level difference among them. Thus we thought out a logical procedure to identify abnormal noise: draw a level at a threshold value in each of these waveforms, and then evaluate the area made by the waves that exceed the set level, and if the area reaches a certain level, we take it as an abnormal noise.



Normal noise



Gear sound **Rattling sound**

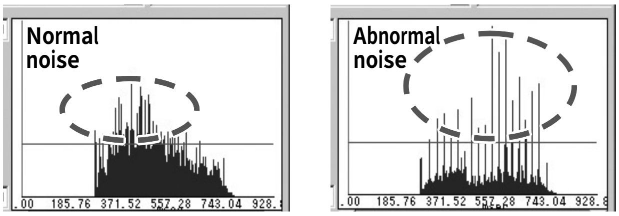
Fig.7 Waveform root squared after emphasizing the 3 to 4 kHz range

3.2 Verification by comparison of projecting area

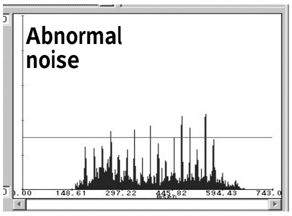
In the practical DU production line, operational noise was recorded from approximately 6,000 units of works and evaluation was performed by means of the area above the threshold level. The result is shown in Figure 8. However, we encountered a number of cases in which:

- **Projecting area is the same for normal noise and abnormal noise, and**
- **Abnormal noise has a smaller projecting area.**

This indicates that our tentative theory that "Abnormal noise has a larger projecting area" does not always stand. This is because the frequency components that make up a sound and the combination of the sound pressures are different, and it is difficult to correctly identify an abnormal noise simply using a certain threshold value.



Projecting area is the same for normal noise and abnormal noise



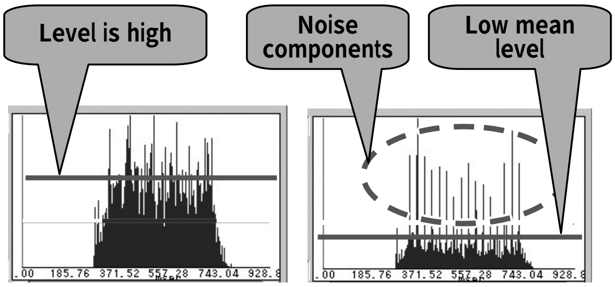
Abnormal noise with smaller projecting area

Fig.8 Judgment by exceeding area

3.3 Digitization of sound features

To perform sound analysis from a new approach, we took note of "Level variation against the time axis". When we compared waveforms, the "Apparent shape" of normal noise and abnormal noise was often different, and as shown in Figure 9, different types of abnormal noise have different patterns:

- **Gear sound has a high level on the whole.**
- **Rattling sound has a low mean value, but involves more intermittent noise components.**



Gear sound **Rattling sound**

Fig.9 Waveform comparison

Since the waveforms of collected sound data have various shapes and sizes, features were extracted at points shown in Figure 10, and data was digitized. Calculation was made using the following equations:

A: The average of the whole waveform (S_{Avg})

$$S_{Avg} = 1/n \sum S_n$$

where

S_n : The level for each one sample

n : The number of samples throughout the waveform

B: The average of mount higher than the level, A, (S_{MaxAvg}; "i" is arbitrary)

$$S_{MaxAvg} = 1/i \sum_{k=max-l}^{Max} S_n$$

C: The number of mounts higher than level, B

D: The area projecting from A (S_A)

$$S_A = \sum S_a$$

where

S_a : The area higher than the area A, for one sample

E: The ratio of A to B (R: The degree of projection from the average value)

$$R = S_{MaxAvg} / S_{Avg}$$

If we use this method, various sounds can be expressed by the combination of five types of numerical data, A to E. Thus, even some different sounds that humans hear similarly can be understood as different numerical data, allowing us to distinguish them more precisely, and we found this a very effective method to detect abnormal noise.

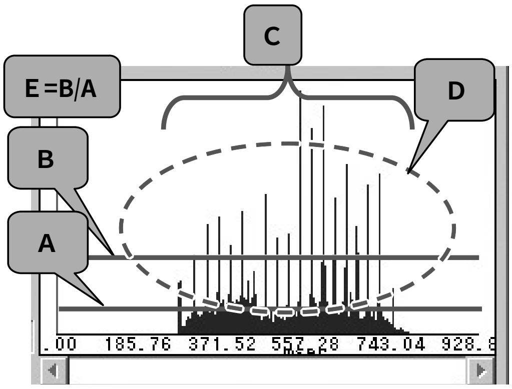
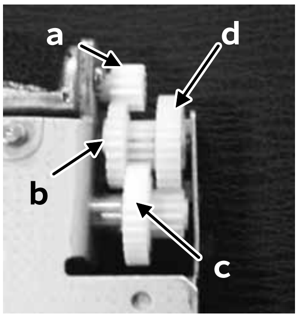


Fig.10 Numerical data

3.4 Types of abnormal noise and features

As previously mentioned, abnormal noise is produced mainly by gear flaws or mixed foreign objects, where the different gears cause different types of abnormal noise. A gear train of DU consists of four gears, a to d, as shown in Figure 11, and if each gear has any dent or other flaws or foreign objects mixed, abnormal noise will sound like as shown in Table 2.



Gear a is press-fit in the motor, and the torque is transmitted to b, to c, and then to d. Revolving speed is the highest at a, and the speed is reduced to b, and c, and then to d.

Fig.11 DU gear example

Table 2 Types of noise per gear

	Type of abnormal noise	Features
Gear a	Gear sound	Scratching sound, catching ears, with the sound pressure being high
Gear b	Gear sound	Sound pressure is a little lower than the abnormal noise from gear a.
Gear c	Rattling sound	Noise components is recognizable although sound pressure is low.
Gear d	Rattling sound	This noise remarkably catches ears, with sound pressure being high.

Those sounds, expressed in waveforms, are shown in Figure 12. Abnormal noise of the same type appears different in the waveform, and resulting numerical data is also different accordingly.

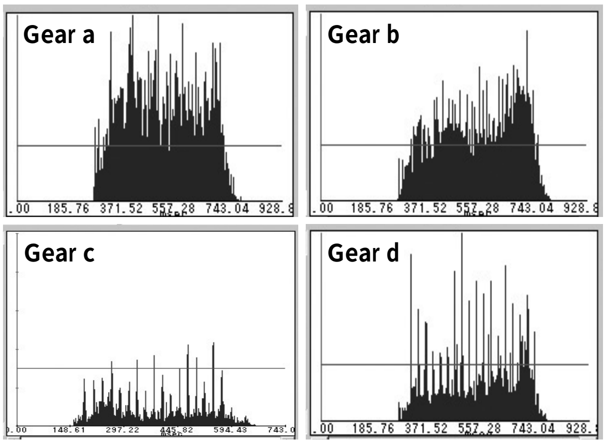


Fig.12 Waveform when gears are abnormal

3.5 Method of evaluating abnormal noise

As described in the previous sections, the sounds collected via microphone were subjected to root-mean-square process, and different waveforms were classified into five groups of numerical data, allowing us to distinguish between the sound types. As a practical matter, however, if we are to discriminate abnormal noise from normal one, we have to define judgment standard to identify abnormal noise when we obtain it; that is, at what numerical data we should identify. The term "judgment standard" we use here means combinations of five types of numerical data. In our study, we used the sound data collected beforehand from 6,000 units of works. Numerical data has the following patterns depending on the types of abnormal noise.

- **Gear sound: A, B and D are large and C and E are small.**
- **Rattling sound: C, D and E are large and A and B are small.**

The above are patterns obtained from a case in which abnormality is found in a single gear, but in practice, abnormality may be found in two or more gears, and therefore, combined gear sound and rattling sound are very likely to exist.

In addition, users' audibility may mind or do not mind the noise depending on the sound types, even with a sound pressure of similar level, and therefore, we will require more precise analysis to evaluate abnormal noise. This should progress in the following steps:

①Setting of boundary samples for abnormal noise

Prepare a DU that actually emits abnormal noise, and set a sample that works as the limit for audibility as a boundary sample.

②Sampling of abnormal noise data

In comparison with the boundary samples, extract only abnormal noise data by comparing to sound data from the 6,000 units by audibility.

③Calculation of characteristics

Calculate numerical data for A to E from each set of abnormal noise data.

④Classification of abnormal noise

Classify abnormal noise of the identical combination of numerical data into groups.

⑤Setting of judgment standard

Decide combinations of numerical data so that all sounds in a group will be detected as an abnormal noise.

The above operations were carried out and data was analyzed in details, and as a result, abnormal noises were classified into 18 types, and we established evaluation judgment standard as listed in Table 3.

Table 3 Judgment standard list per abnormal sound group

	Judgment standard involving numerical data				
Group No.	A	B	C	D	E
1	≧ 18	≧ 20	—	—	—
2	≦ 8	≧ 18	≧ 8	≧ 800	≧ 4.5
3	≦ 3.2	≦ 15	≧ 8	≧ 500	≧ 4.3
4	≦ 3	8 - 15	≧ 7	≧ 250	≧ 4.5
≀	≀	≀	≀	≀	≀
18	≦ 2	5 - 10	≧ 7	≧ 300	≧ 4

3.6 Algorithm of evaluation

To evaluate and determine a sound to be an abnormal noise or not, convert the sound into numerical data, then apply the judgment standard of group No.1 in Table 3 and compare the values, and then go to judgment standard of the next group, in turn. If the sound fails to meet all judgment standard of 18 types, take the sound as a normal noise, and if the sound meets the judgment standard of any group No., decide the sound as an abnormal noise. Further, since abnormal noise of each group has different features, we can grasp "What features does the abnormal noise have" in addition to simply evaluating abnormal noises. This enabled us to estimate the point of gear abnormality.

Thus, compared with the previously mentioned simple method of evaluation using the projecting area only, this method expresses a waveform using multiple parameters, therefore providing us with very precise classification of sound. Consequently, it has come to be possible to detect all existing abnormal noises by 100%.

However, all doubtful sounds (including sounds that are evaluated "Passed" through comparison with the boundary sample) were evaluated abnormal noise because of the too strict judgment standard for abnormal noise, and this over-detection resulted in the number of detected nonconformity items several times of actual abnormal noises. Therefore, it is necessary to reduce over-detection.

4 Measures against over-detection

4.1 Causes of over-detection

The numerical data obtained from two waveforms shown in Figure 13 is listed in Table 4. We can discriminate between normal noise and abnormal noise by audibility, but comparison of values offers little difference. This causes the over-detection, taking normal noise for abnormal one.

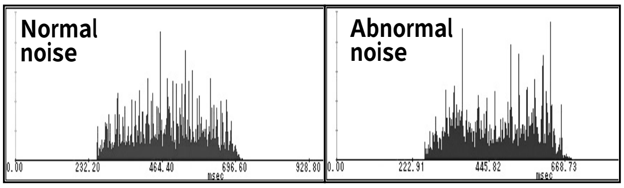


Fig.13 Waveform comparison of normal noise and abnormal noise

Table 4 Numerical data of the waveform in Figure 13

	A	B	C	D	E
Normal noise	4.2	3.7	10	12.1	4.6
Abnormal noise	5.1	4.4	9	42.1	4.7

4.2 Tactics for reduction of over-detection

If a noise sounds like an abnormal noise, it means that the noise contains many of frequency components in which human auditory sense functions at high sensitivity. When you cannot distinguish between normal noise and abnormal noise even if you compare numerical data as mentioned above, then apply a band pass filter (hereafter, BPF) to the noise and take out only that band, and it will become possible to distinguish them. Figure 14 shows the result of two waveforms in Figure 13 subjected to a BPF of 10 to 20 kHz, and Table 5 shows the result of the waveform in Figure 14 subjected to digitization.

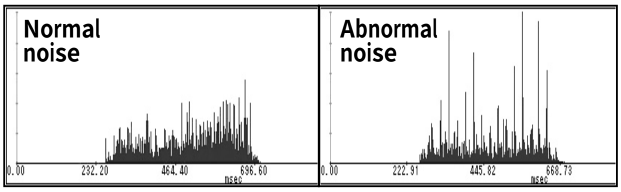


Fig.14 Waveform after passing BPF

Table 5 Quantified characteristics (after passing through BPF)

	A	B	C	D	E
Normal noise	1.7	1.8	5	0	3.8
Abnormal noise	2.7	1.7	9	26	6.4

The above evidently shows clear difference occurring in the shape of waveform and numerical data (C, D and E). Provision of such processing could elevate the accuracy of discrimination of abnormal noise.

4.3 Algorithm of evaluation that reduced over-detection

In addition to the simple evaluation of abnormal noise

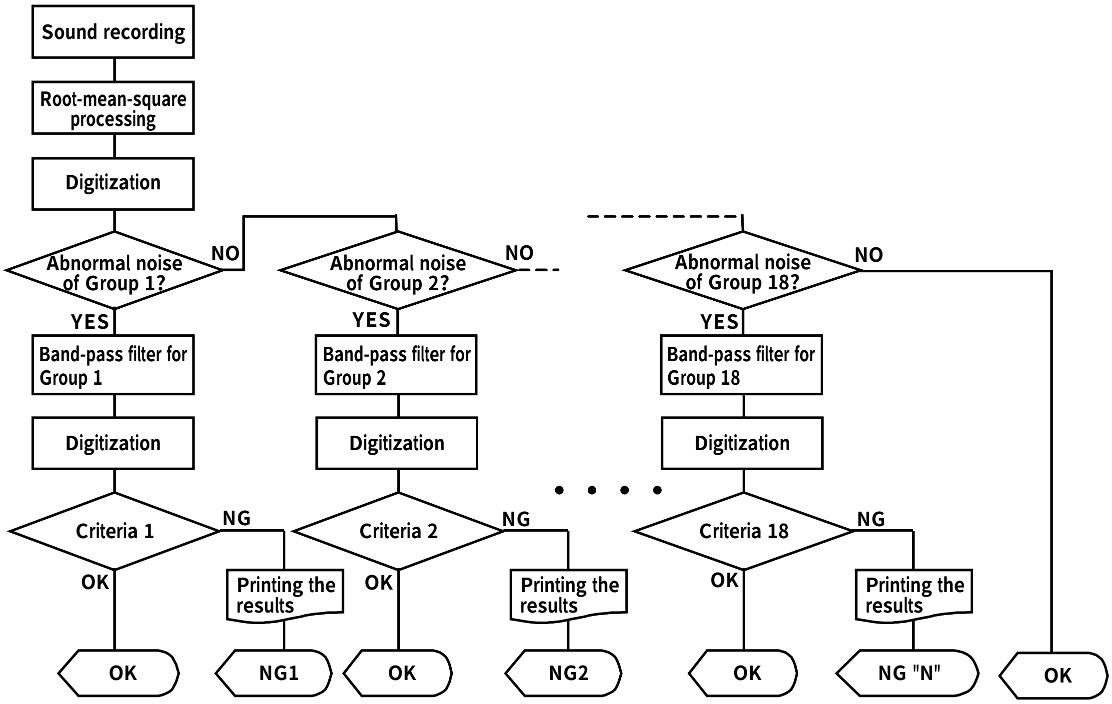


Fig.15 Abnormal noise identification algorithm

only by the judgment standard for each group, as mentioned above, apply a BPF to the noise, then use digitization again, and exercise data comparison, and this allowed us to more accurately evaluate abnormal noise.

This evaluation algorithm is shown in Figure 15. This algorithm helped us clear the over-detection level, the initial target.

5 Development of inspection device

To realize inspection of abnormal noise in a practical manufacture process, we were required to develop an automatic machine that incorporate the algorithm as in the previous section. This section describes the details of the development.

5.1 Detection of abnormal noise in a practical production line

The noise level in the production line of the Company is 60 to 70 dB (A). However, the search sound of the drive unit is approximately 50 dB (A) at a position 50 mm away from the subject for measurement in a quiet environment such as an anechoic chamber. In the environment of production line, therefore, the DU is totally buried in the ambient sounds as shown in Figure 16.

Now, we decided to use a sound shield box to achieve stable inspection. However, anechoic chambers and marketed anechoic boxes involved problems such as too big size, expensive, difficult to modify it into an automatic machine, and therefore, we tried to develop a sound shield box.

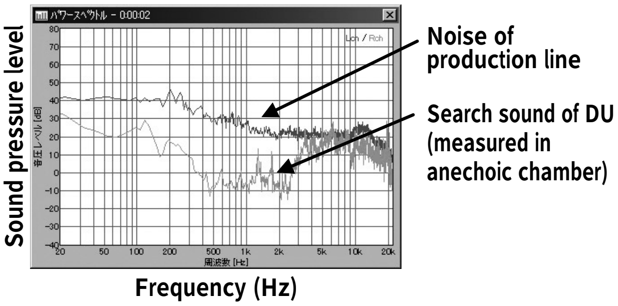


Fig.16 Frequency characteristics in the production line environment (peak hold)

5.2 Materials and structure of sound shield box

For outside wall of sound shield box, we adopted porous aluminum used in sound insulation wall, etc. as shown in Figure 17. Taking into account the workability in the production line, and for the front, an automatically operated sliding door was adopted in the structure as shown in Figure 18.

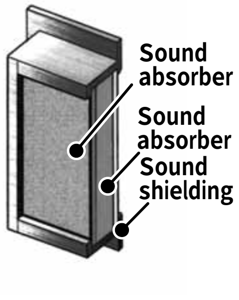


Fig.17 Sound shielding

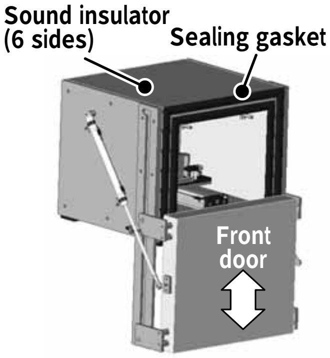


Fig.18 Sound shield box construction

5.3 Characteristics of sound shield box

However, a sound shield box, only combined with sound insulator, was cost, but as shown in Figure 19, sound insulation was poor against external noise of low frequency (about 500 Hz and lower), and low frequency sound such as carriage traveling sound, etc, together with the action sound, was recorded during inspection, and it appeared as a waveform, as shown in Figure 20. Once the noise appeared as a waveform, in the abovementioned evaluation algorithm, it was digitized, likely to cause wrong evaluation. Therefore, we examined the frequency band that was necessary for evaluation, and found that 1 kHz or lower band was low in the contribution to evaluation, and we used filter processing to eliminate 500 Hz or lower band as a measure. The waveform after filter processing was shown in Figure 21.

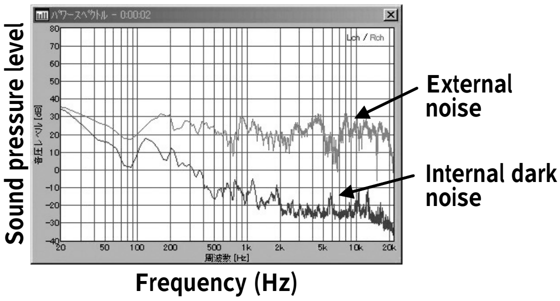


Fig.19 Background noise level in sound shield box

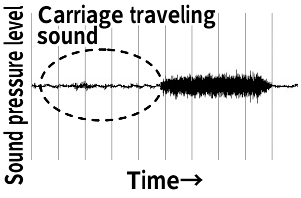


Fig.20 Source waveform

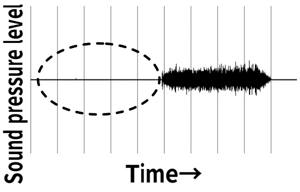


Fig.21 Waveform after filter processing

5.4 Realization of automatic machine

Although we have come to a hope of detecting abnormal noise also in the environment of production line, we have to make an automatic machine to use a device in the actual production line. Therefore, we assembled the algorithm described in Section 4.3 in our standard inspection system as an "abnormal noise inspection module". Then we completed a device of automatic machine, using a programmable logic controller (PLC) to control automatic door operation, and the action of work setting part.

5.5 Assembly in a standard inspection system

In the inspection process of Ten's production line, a Windows Flexible Test System (WFLEX) is used as a standard inspection system. WFLEX is an inspection system that Fujitsu Ten developed, and it is an "integrated processing system" that can complete processing through an arbitrary combination of data of two or more modules.

We developed a program for the algorithm of evaluating abnormal noise, that we developed this time, as an "abnormal noise inspection module" shown in Table 6, and assembled it in WFLEX. And then, as shown in Figure 22, we combined an "abnormal noise inspection module" and existing modules, and we completed an automatic abnormal noise inspection device that can achieve the flow chart shown in Figure 15. Further, we could restrain the development man-hours and cost for the entire system by utilizing existing modules.

Table 6 Abnormal noise inspection module

Modules	Function
Recording module	To record operational noise
Converting module	Root-mean-square processing of recorded data
Digitizing module	To digitize waveform
Evaluating module	To reduce over-detection and evaluate pass/fail
Other	Calibration, etc.

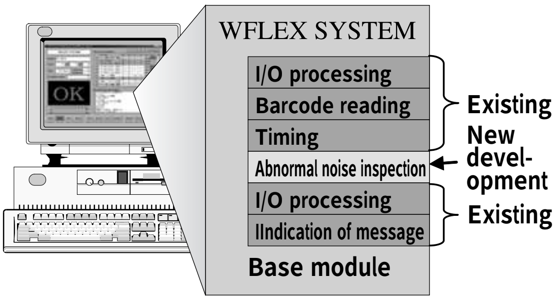


Fig.22 Noise inspection by the WFLEX system

5.6 Outline of automatic abnormal noise inspection device

The composition of automatic abnormal noise inspection device integrated in the WFLEX system is shown in Figure 23, and specifications are listed in Table 7 while Figure 24 shows a photograph of device actually mounted in the production line.

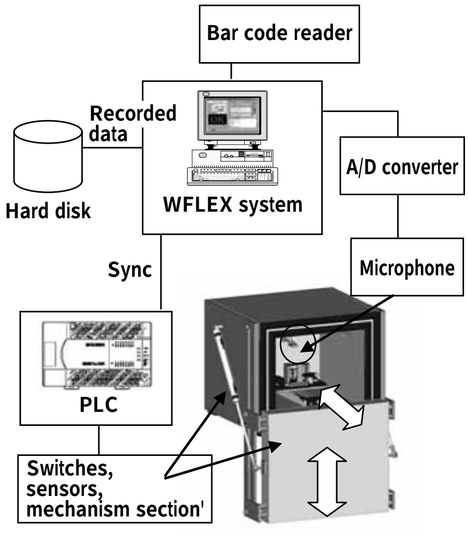


Fig.23 Structure of the automatic noise inspection equipment

Table 7 Automatic noise inspection equipment specifications

Work for inspection	Search sound of DU
Outside size/weight	Approx. 700 (W)×750 (D)×1400 (H); approx 150 kg
Major components	Platform + sound shield box, WFLEX PC; recording microphone, A/D converter
Control system	Inspection and evaluation: WFLEX system; mechanism drive: PLC
Dark noise	Internal dark noise: 40 dB (A) or less when external noise is 70 dB (A)
Process and cycle time	Approx. 35 sec Details: ・Set of product ・Bar code reading ・Automatically inspection (20 sec) ・Picking up product

Fig.24 Automatic noise inspection equipment introduced in an actual production line

5.7 Analysis supporting functions

This device is provided with a function to store the sound data of the works for inspection together with the products serial number in the hard disk when recording / evaluating. Further, we can check the sound in a relevant remote office(s) other than inspection site if any trouble arises because this system is connected to the corporate LAN as shown in Figure 25.

Through the operation of the above said system, we can immediately understand what sort of abnormal noise is occurring even when the actual article of the trouble is not at hand, and moreover, it is possible to make the most of the system as an analysis supporting tool such as comparison with the past trouble cases and trend analysis, to ensure prevention of abnormal noise.

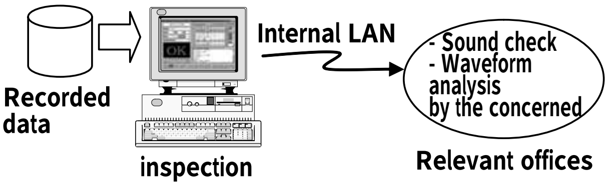


Fig.25 Analysis support using the company LAN

6 Result of development and future problems

6.1 Result of development

The introduction of automatic abnormal noise inspection device, in the production line enabled us to detect abnormal noise in the DU assembly process, which we could not in the past, allowing us to prevent defective works from outflowing to next processes.

In addition, it has become possible to identify troubling cases that were handled in a single category of "Abnormal Noise" in the past, in the light of "what kind of abnormal noise", specifically by means of recorded data, waveform and numerical value, which ensured that we promote activities for clarification of causes and prevention of recurrence.

6.2 Approach to occurrence prevention

The change of abnormal noise detection before and after the introduction of the system to the production line is shown in Figure 26. The introduction of the system in the DU process drastically elevated the ability of abnormal noise detection by seven times.

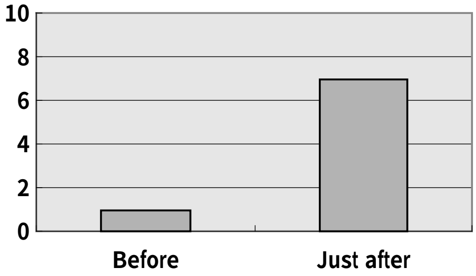


Fig.26 Detection rate before and after the introduction of the equipment

Here, a trend analysis was performed on the actual works of abnormal noise, and this revealed that most of abnormal noises came from specific gear flaws. Investigation of causes found that a jig in the process had a risk of coming into contact with the gear of problem. Therefore, we added an escape hole to secure clearance as shown in Figure 27. Based on the result of trend analysis of abnormal noise, we promoted the trouble prevention activity.

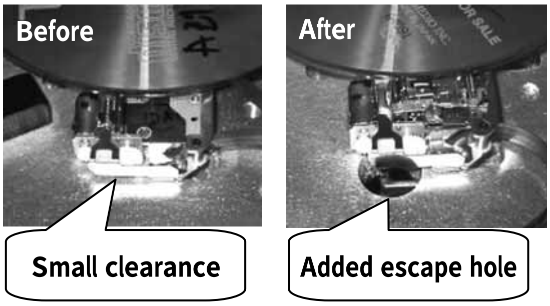


Fig.27 Process improvement example

Consequently, cases of abnormal noise trouble were reduced to one tenth. Also in the subsequent processes, abnormal noise has not been detected any more, and we have achieved both outflow prevention and occurrence prevention.

Furthermore, as shown in Figure 28, a mechanism was built such that the data of a DU that is emitting abnormal noise, as evaluated by the automatic abnormal noise inspection device, is processed by the analysis staff member in the production site to identify the causes of gear flaw, etc., and the obtained data is transferred to the design group via real-time feedback to contribute to design improvement.

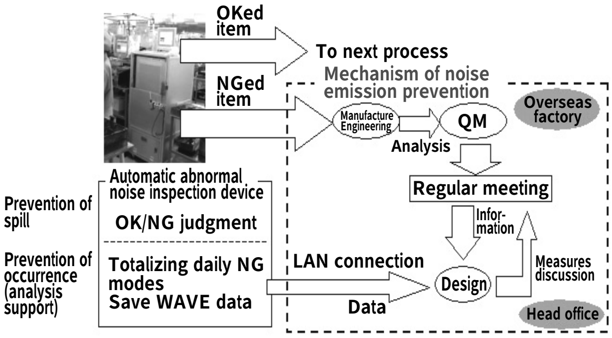


Fig.28 Process for preventing occurrence

6.3 Evolution to other models

The system of abnormal noise inspection that we developed has been put in a practical use in the shape of a module such that it can be incorporated into standard inspection system, facilitating implementation to other models. However, if the type of works for inspection is changed, emitted sound itself also changes and therefore, we must consider the following items to meet each subject work:

①Collection of abnormal noise samples to setting another judgment standard

②Grouping of abnormal noises and setting of judgment standard (numerical data)

In addition, features of the subject noise for detection is not always limited to a simple action such as the search sound, and therefore, it is required to provide optimal algorithm of evaluation in order to cope with sounds that present a more complicated pattern.

Compared to ordinary inspection equipment, therefore, this device has a problem that it requires long time until introduction to practical use because consideration is required such as the above by the type of the work. This point is listed as one of future subjects for improvement.

6.4 Future evolution and challenges in technology development

Taking DU as the subject in our study, we developed a technique to quantitatively evaluate abnormal noise and completed a system of automatic abnormal noise inspection. However, various products including CD deck, DVD deck and display units involve more other parts that emit operational noise such as opening or shutting their lid. In the future, we are planning to promote measures to perform quantitative evaluation for stabilization of inspection quality and prevention of abnormal noise also for other source of abnormal noise as said above.

As previously described, the abnormal noise inspection technology described above, involves some remaining problems, such as it takes time until introduction and it beforehand requires abnormal noise data that underlie the judgment standard and other problems. To solve those problems, we are promoting development of a system in which we first estimate abnormal noise based on normal operational noise, and then establish an evaluation theory.

We will continue technology development so that the process of abnormal noise inspection will be totally automated in near future.

7 Conclusion

We have reported the outline of the method to quantitatively evaluate abnormal noise and the automatic abnormal noise inspection device that we developed. This technique enables us to express sounds in numerical values, and to practice quantitative inspection. In the future, we will promote lateral spreading to other models in a short term in order to better the quality of operational noise.

At the tail of this paper, we express heartful appreciation to concerned people for guidance and collaboration in this development.

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