Sound Quality Discrimination of the Impulsive Sounds with Mahalanobis Distance

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Abstract

Reduction of the acoustic noise emitted by a copier and printer is strongly demanded because of more rigorous noise regulations and higher customer requests. Although to identify the noise sources is important, the conventional technologies to search for the locations of noise sources with phase information do not have enough spatial resolution for the impulse noise. So an analysis method to discriminate between impulse sounds with sound quality characteristics have been studied for identification of noise sources. As the results, the following conclusions were gotten. (1) A new method to discriminate between impulse sounds by utilizing a statistical analysis of sound quality was devised, which directly expands each data on the acoustic waveform to Mahalanobis space and compares spatial distances. (2) It was shown that four types of simulated impulse sounds emitted from paper transport systems could be discriminated with accuracy of 90%. (3) It was clarified that how to normalize waveforms on the time axis was important to improve the discrimination accuracy. (4) Mahalanobis distance has continuous and monotonous characteristics corresponding to the differences between waveforms.

Introduction

Recently, it is demanded to reduce the noise emissions of office printers and copiers because our workplaces have become quiet. Rigorous noise regulations, such as Blue Angel in Germany[1] and Ecomark in Japan, to office equipment have been instituted in many countries. The reduction of impulse noises is necessary in particular because it produces big sound pressure in a short time and gives us big unpleasantness. To identify the noise sources is the first step for reduction of noise emissions, but it is difficult because the impulse sound has too short duration and too large wavelength to analyze precisely. Therefore, we tried to deduce the noise sources with a sound quality analysis of the noise waveform. Concretely, we investigated a statistical discrimination with Mahalanobis distance that is one of spatial distance measures.

In this paper, we verify validity of the statistical method and possibility for discrimination between impulse noises. As the first step, we show the discrimination results on four kinds of simulated impulse sounds.

Statistical Analysis of Sound Quality

Mahalanobis Distance

Mahalanobis distance is one of spatial distance measures in the multivariate space and has a unique characteristic to calculate the distance based on the correlation between variables.[2] Then it is often used on the statistical discrimination analyses. Several studies with Mahalanobis distance, for example a diagnosis of physical condition with many health checkups[3] and a discrimination of a fire-hazard with many smoke sensors, were addressed in the literature.

Direct Expansion of Waveform Data

In general, many useful characteristics are defined and measured beforehand and are expanded to Mahalanobis space. However, useful characteristics for the impulse sound of printers and copiers are not yet clarified. Therefore, we considered each sound pressure value on the impulse noise waveform to be multivariate values, and tried to expand them directly to Mahalanobis space.

Description of Experiments

Types of Impulse Sound

Sound of Paper Edge Collision

This sound simulates one of the major paper noises. The noise is supposed to be emitted when a leading edge of paper collides to a driving roll. A sheet of paper was dropped and collided to a plastic plate vertically, and the sound emission with collision of the paper edge was captured.

Sound of Flicking Paper End

This sound simulates another major paper noise. The noise is supposed to be emitted when the rear edge of paper was flicked at a step on the paper transport path. A metal plate flicked an edge of paper gripped between a pair of plastic plates, and the flick sound of paper was captured.

Mechanical Sound

This sound simulates the noise of clutch and solenoid to activate the paper transport systems. The metal and plastic plate adhered on a rigid surface are hit with a plastic drumstick, and the impact sound was captured.

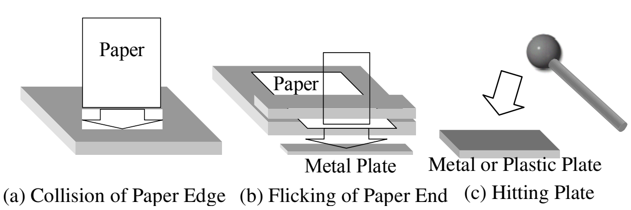

Figure 1. Methods to generate impulse sounds

Capturing Acoustic Waveforms

The impulse sound was recorded in the semi-anechoic room with the recording system of Fig. 2, and it was taped to a DAT recorder in sampling frequency of 48kHz. Four types of sounds, 200 samples each, were taped. A-weighted filtering is applied on the captured sounds to remove unnecessary components that have no influence to the human acoustic sense.

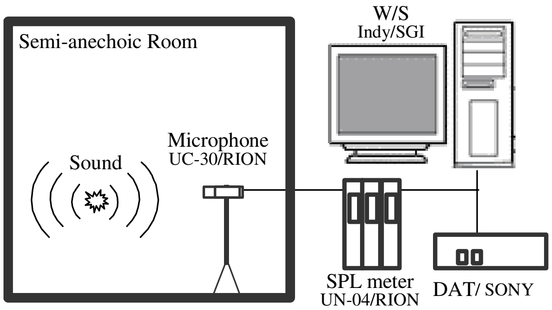

Figure 2. Recording system of impulse sounds

Time Scaling of Waveform

In Mahalanobis space, the order relation between variables is not considered. So it is afraid that characteristics such as periodicity are not detected when the waveforms are treated with no attentions to temporal information. Therefore, we tried to adjust the phase of waveforms by setting a reference point on the time axis. The starting point was searched by scanning the waveform from beginning, and 80 points of data consisting of 10 points before the starting point and 70 points after it were captured.

Defining the Reference Space

At first, a reference group to define Mahalanobis space is decided. An arbitrary group can be defined as the reference. A group of hitting metal plate was defined as the reference space here. More than 80 samples, the number of variables, are necessary to calculate the inverse matrix of a correlation coefficient matrix between all variables. The reference space was defined with 100 samples extracted from all 200 samples at random here.

Calculation of Mahalanobis Distance

The waveform is normalized with mean values and standard deviations of 100 samples about each 80 variable, and displayed in a matrix as the vector Yij.

$$Y_{ij} = \begin{pmatrix} Y_{1,1} & \cdots & Y_{1,80} \\ \vdots & \ddots & \vdots \\ Y_{150,1} & \cdots & Y_{150,80} \end{pmatrix} \qquad y_{ij} \rightarrow Y_{ij} = \frac{y_{ij} - \bar{y}_j}{\sigma_j} \tag{1}$$

The correlation coefficients are calculated about 3160 (${}_{80}C_2$) pairs between all variables in Eq. 2, and the correlation coefficient matrix is formed.

$$r_{pq} = r_{qp} = \frac{\sum (Y_{ip} \cdot Y_{iq})}{\sqrt{\sum Y_{ip}^{\ 2} \cdot \sum Y_{iq}^{\ 2}}} \tag{2}$$

Then the inverse matrix of the correlation coefficient matrix is calculated.

$$A = \begin{pmatrix} a_{1,1} & \cdots & a_{1,80} \\ \vdots & \ddots & \vdots \\ a_{80,1} & \cdots & a_{80,80} \end{pmatrix} = R^{-1} = \begin{pmatrix} 1 & \cdots & r_{1,80} \\ \vdots & \ddots & \vdots \\ r_{80,1} & \cdots & 1 \end{pmatrix}^{-1} \tag{3}$$

The Mahalanobis distance is calculated finally with Eq. 4.

$$D^2 = \frac{1}{80} \begin{pmatrix} Y_1 & Y_2 & \cdots & Y_{80} \end{pmatrix} \begin{pmatrix} a_{1,1} & \cdots & a_{1,80} \\ \vdots & \ddots & \vdots \\ a_{80,1} & \cdots & a_{80,80} \end{pmatrix} \begin{pmatrix} Y_1 \\ \vdots \\ Y_{80} \end{pmatrix} \tag{4}$$

Experimental Results

Discrimination between Mechanical Sounds and Paper Sounds

A reference space was defined with the sound of hitting a metal and plastic plate, and the discrimination between the sounds of mechanical and paper was examined. Half of the mechanical sounds and all the paper sounds were allocated for verifying. Figure 3 shows the calculation results of the Mahalanobis distance. There is great difference of two or three digits between the mechanical sounds and paper sounds, and they can be completely discriminated.

Discrimination between Mechanical Sounds

The discrimination of the impact sounds of plastic plate was tried by comparing with the impact sounds of metal plate as the reference space data. There was more than a digit difference between two groups on average, but several data around the border of two groups overlapped (Fig. 4). Discrimination accuracy was 96.0 % when a temporary threshold was set to 10 on the Mahalanobis distance.

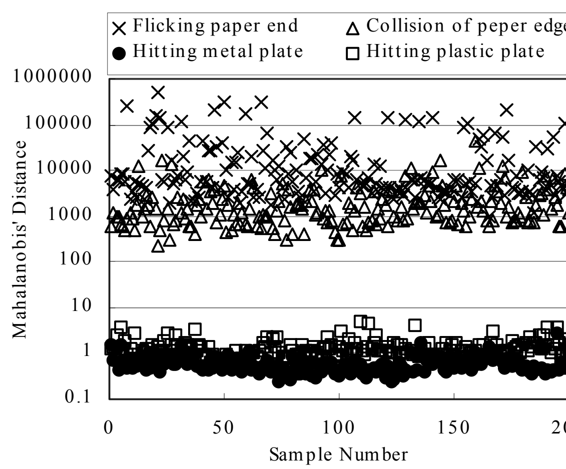

Figure 3. Mahalanobis distance on discrimination between mechanical sounds and paper sounds

Discrimination between Paper Sounds

The flicking paper sounds were discriminated by using the paper collision sounds as the reference data. Difference between two groups was recognized on average, but many data mingled each other around the border (Fig. 5). Eight samples in all 400 samples were discriminated incorrectly if a temporary threshold was set to 10 on the Mahalanobis distance, and the accuracy was 90.5%.

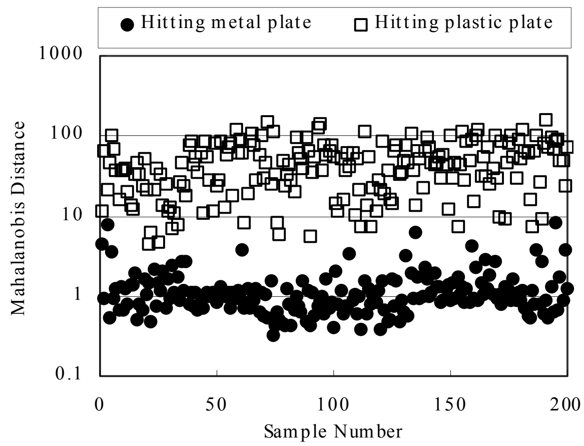

Figure 4. Mahalanobis distance on discrimination between the mechanical sounds

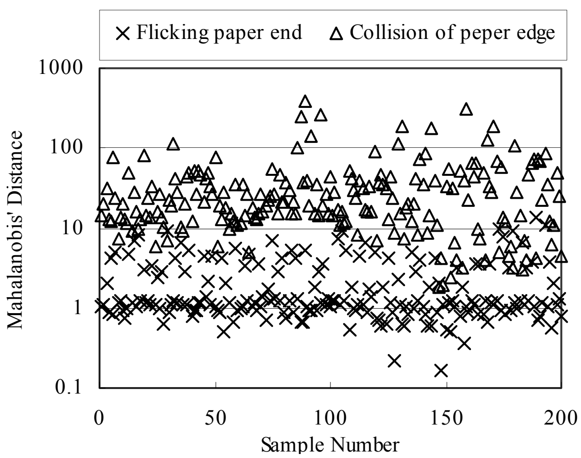

Figure 5. Mahalanobis distance on discrimination between Discrimination between paper sounds

Discussion

Appropriate Number of Data for Discrimination

The discrimination between the mechanical sounds was repeated with changing the number of variables (waveform data) to investigate the appropriate number of data for discrimination. "The margin for discrimination" expressed in Eq. 5 was defined as the evaluation index.

$$Mergin = \frac{D_{min.}}{S_{mean} + 2 * S_{std.}} \quad (5)$$

Here, S_{mean} is the mean value of D^2 in the group same to the reference, S_{std} is the standard deviation of them, and D_{min} is the minimal value of D^2 in the other group. If this margin is more than one, it is statistically expected that the discrimination accuracy exceeds 95%. Fig.6 shows the results. The margin was improved gradually in range to 50. Then, it was saturated and turned slightly worse adversely. These results suggest that excessive increase of the number of data is not significant. This reason is considered as follows. As the fluctuation of temporal characteristics, for example periodicity, was accumulated gradually, The effect of adjusting waveforms at the start time was lost on the condition of excess numbers of data.

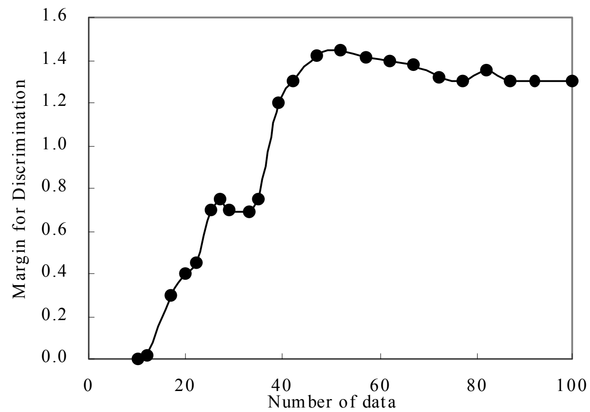

Figure 6. Effect of number of data for discrimination

Multiple Discrimination

Experiments of Multiple Discrimination

Mahalanobis distance is mainly used for the discrimination between two groups. Therefore, multiple and step-by-step discriminations are needed for the discriminations among more than three groups. Here, we investigate the possibility of discriminating between more than three groups on the single Mahalanobis space.

The Mahalanobis distances of all four types of impulse sounds were calculated by using the impact sounds of the metal plate as the reference space. Figure 7 shows the results. It was classified roughly by three groups of the impact sound of the metal plate, the impact sound of the plastic plate, and two other paper sounds. As for the discrimination between the two types of paper sounds, the difference of about one digit was recognized on average although the data around the border mingled. The distance became larger in order of metal, plastic, collision of paper (compression direction), and flicking of paper (bending direction). It depends on the stiffness of material to be hit, and the lower the stiffness is, the larger the distance becomes. It is considered that it has physical rationality.

Temporary thresholds were determined from the average distance of each group, and each discrimination rate was calculated. Table 1 shows the results. It was confirmed that multiple discrimination was possible with the accuracy of around 80%.

Table 1: Validity on the Multiple Discrimination

The groups to be discriminated	Rate
Between the mechanical sounds	98 %
Between the mech. sounds and the paper	100 %
Between the paper sounds	83 %

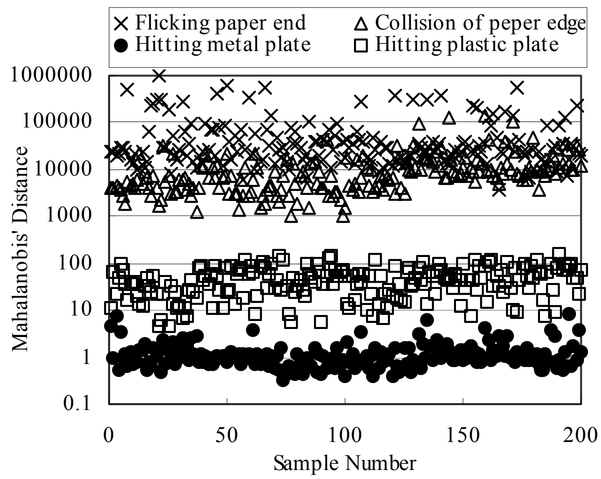

Figure 7. Mahalanobis distance for multiple discriminations

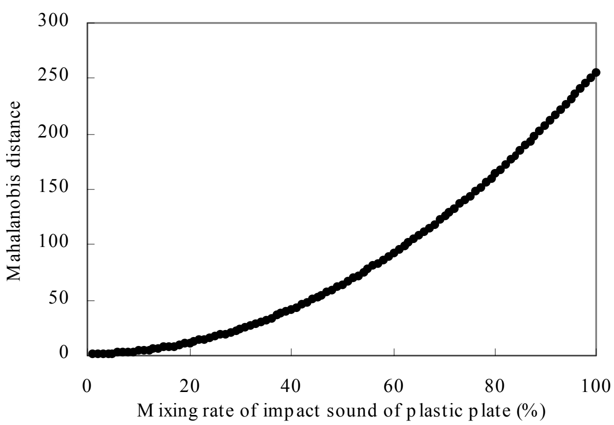

Figure 8. Behavior of Mahalanobis distance depend on the mixing rate of waveforms

Behavior of the Mahalanobis Distance

It must be clarified that the Mahalanobis distance has continuity and monotonicity on the multi-dimensional space defined with many factors to verify the realizability of multiple discrimination. As one case study, artificial waveforms were made with mixing the impact sound of the metal plate and that of the plastic plate at various rates, and it was examined what kind of behavior the Mahalanobis distance showed. Figure 8 shows the results. The Mahalanobis distance increased monotonously depending on the mixing rate. These results suggest that Mahalanobis distance has continuity and monotonicity depending on the similarity of waveforms, and that the multiple discrimination with Mahalanobis distance has validity and rationality.

Conclusions

(1) We proposed a new analysis method for impulse sounds in which the acoustic waveforms are directly expanded to the Mahalanobis space.

(2) It was confirmed that four kinds of impulse sounds, which simulated the noise emitted from the paper transport system, could be discriminated with about 90% accuracy experimentally.

(3) It was clarified that Mahalanobis distance has continuity and monotonicity depending on the similarity of waveforms, and that the multiple discrimination on single Mahalanobis space was possible.

References

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Author Biography

Koji Udagawa holds a BS degree in Electronics and Information Engineering from Yokohama National Univ.(1984) In 1984, he joined Fuji Xerox Co., Ltd., where he has been engaged in research on manufacturing engineering of printed wiring boards. He has worked on study of acoustic noise emitted from copier/printer since 1992 and currently takes charge of noise reduction, evaluation, and analysis.