Verification of contribution separation technique for vehicle interior noise using only response signals

Tomohiro HIRANO[1]; Junji YOSHIDA[1]

[1] Osaka Institute of Technology, Japan

ABSTRACT

In this study, a contribution separation technique using only response signals were considered for an analysis of vehicle interior noise. Independent component analysis (ICA) was applied for the technique. To verify and consider the applicability of the method in contribution separation, vehicle engine, road, and wind noise sources were combined artificially to simulate vehicle interior noise and applied ICA to these signals for contribution separation. The result shows the contribution could not be obtained correctly by the permutation problem in which the correspondence relationship between calculated and actual contributions is not kept along frequency. A solution technique was then proposed to solve the problem using the characteristics of sound source. As a result, the technique with the method could calculate accurate sound source contributions using only response signals.

Keywords: Contribution analysis, Independent component analysis, Permutation problem
I-INCE Classification of Subjects Number(s): 74.6

1. INTRODUCTION

Improving vehicle interior noise levels is essential to achieve comfortable cabin conditions. During this process, the increase in vehicle weight should also be minimized in order to make the noise performance compatible with the driving performance and the fuel efficiency. To achieve these goals, it is important to determine the contributions of a range of different factors to vehicle interior noise such as engine and road noise to perform countermeasure sound sources having high contribution intensively.

To obtain the contributions for interior noise, transfer path analysis (TPA) technique was developed, and several TPA methods have been proposed until now (1-5). In the TPA technique, input or reference points signals are necessary to be measured to obtain input signals, and the signals are multiplied with transfer function for calculating the contribution. This method enables us to obtain contributions in detail even if there are many transfer paths by measuring each input point signal and transfer path. Thus, TPA technique was applied many times in vehicle developments to perform countermeasure of vehicle interior noise effectively. On the other side, if defining an input position in the vehicle is uncertain such as wind noise, applying TPA technique is difficult. In addition, in case setting an acceleration sensors or microphones around input points is difficult by the restriction of the space or temperature, it is also hard to use this technique.

Accordingly, our research group has carried out basic studies about a contribution separation technique which does not need to take any input signals and transfer functions. We proposed a contribution separation technique using ICA (6) and applied the technique to a simulated vehicle interior noise which consists of two major sound sources (engine and wind noises / road and wind noises) (7, 8). These two sound sources could be separated well by applying the proposed method with an original permutation solver (7, 8).

On the other hand, vehicle interior noises are generally composed of three sources: engine, road and wind noises, and there are many cases in which the contributions of all sound sources are significant simultaneously in an actual driving condition. However, it is unknown our proposed

[1] yoshida@med.oit.ac.jp

contribution separation technique using ICA has an ability to separate these three contributions accurately.

In this study, we considered an analysis method which can separate contributions of the three sound sources using only response signals without any input signals by expanding our prior ICA technique through a simple simulation.

2. INDEPENDENT COMPONENT ANALYSIS

Independent component analysis (ICA) is a signal processing method which enables to extract sound source signals from mixed response signals without using any source signals (6). The basic idea of ICA is described below.

Relationship between multiple sound source matrix [*s*] and multiple mixed (observed) response signal [*x*] is expressed by using the mixing matrix [*A*] as follows.

$$[x]=[A][s] \tag{1}$$

Sound source matrix [*s*] and mixing matrix [*A*] are estimated from only observed matrix [*x*] in the ICA procedure. When the sound source signals are independent each other and have non-Gaussianity, the distribution of the mixed signal changes from non-Gaussian to Gaussian by the central limit theorem (6). In the ICA procedure, separation matrix [*W*] (= $[A]^{-1}$) is calculated by optimization theorem and separation signal (estimated source) [*y*] could be described as follows.

$$[y]=[W][x] \tag{2}$$

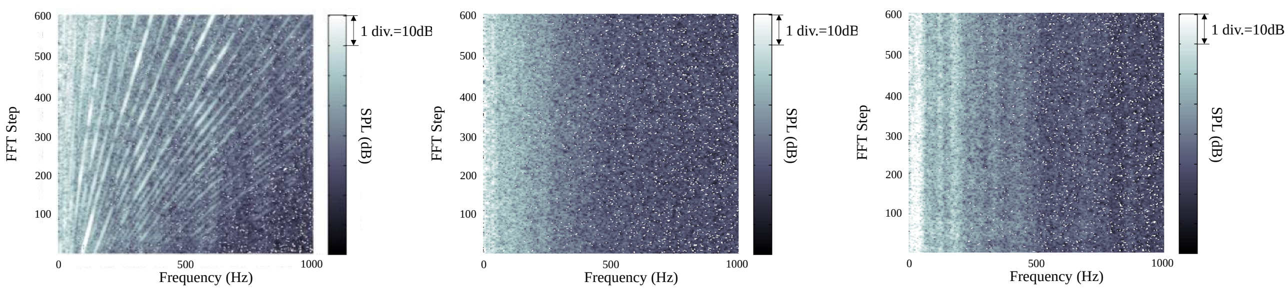
We have applied this ICA method as the analytical method for contribution separation of vehicle interior noise (7, 8). There are two types of ICA method. First one is time domain ICA, which is applied time domain mixed signals, and the other one is frequency domain ICA, which is applied frequency domain mixed signals. Here, we tried to apply the frequency domain ICA, because it was reported that the method could extract sound source even if the sound sources were synthesized with transfer time gap and the method could separate contribution of vehicle interior noise better than time domain ICA in our previous studies (7, 8). As the calculation algorithm to obtain separation matrix [*W*], Complex-JADE which can be applied to Fourier transformed complex signals was employed (7-9).

3. VERIFICATION USING A SIMPE SIMULATION

3.1 Sound sources

To verify reliability of contribution separation using ICA, engine, wind and road noises were employed as the contribution separation targets. As the engine noise, an interior sound recorded at rapid acceleration condition on a smooth road, which is considered to have little influence of road and wind noises, was employed. As the wind noise, an interior noise recorded at cruising condition over 100 kph on a smooth road, which is considered to have little influence of engine and road noises, was employed. And, an interior noise recorded at cruising condition under 100 kph on a rough road, which is considered to have little influence of engine and wind noises, was employed as the road noise.

Figure 1 shows the contour diagrams of each recorded signal.



(a) Engine noise source (b) Wind noise source (c) Road noise source

Figure 1 – Contour diagrams of recorded sound source signals

Horizontal and vertical axes indicate frequency and FFT step, respectively, and hue shows sound pressure level.

Figure 1 (a) shows the FFT result of the acceleration noise. From the result, this noise is observed to be dominated by rotational order components of engine. Henceforth, this noise was employed as the engine noise source for the following simulation. Figure 1 (b) shows the result of the noise recorded at cruising condition over 100 kph on smooth road. The result shows that the noise is dominated by random components, which is representative characteristic of wind noise. This noise was therefore employed as the wind noise source. Figure 1 (c) is the result of the noise recorded at cruising condition under 100 kph on rough road. The noise was dominated by low frequency noise, which is a characteristic of road noise. The noise was used as road noise source.

3.2 Verification procedure

Actual contribution of each sound source was made by multiplying voluntary weighting factors with sound sources in time domain. The mixed signals (simulated interior noise) were then composed by adding the contributions with different time gaps considering the actual transfer situation. Three simulated interior noises were made using the identical sound sources with different weighting factor and time gaps. These three signals were regarded as the interior noise measured at three different positions. In the verification, contribution of these simulated interior noises would be calculated by ICA. In addition, the contributions in narrow frequency bands are converted to 1/3 octave bands to avoid accuracy decrease by the variance shortage of recorded sound pressure in a narrow frequency proposed in our previous study (8). The contribution calculation procedure is described below.

1. Dividing mixed signals (simulated vehicle interior noise) to each FFT block
2. Iterating FFT to the separated time block of the mixed signal
3. Making an observation signal matrix consisting complex number in each frequency (the number of row: the number of mixed signals, the number of column: the number of FFT iteration number)
4. Performing ICA to the matrix in each frequency
5. Obtaining contributions by multiplying calculated sound source signal with mixing matrix in each frequency

To evaluate the accuracy of the calculated contribution by ICA, the calculated contribution was compared with the actual contribution. The outline of the verification procedure is shown in Fig. 2.

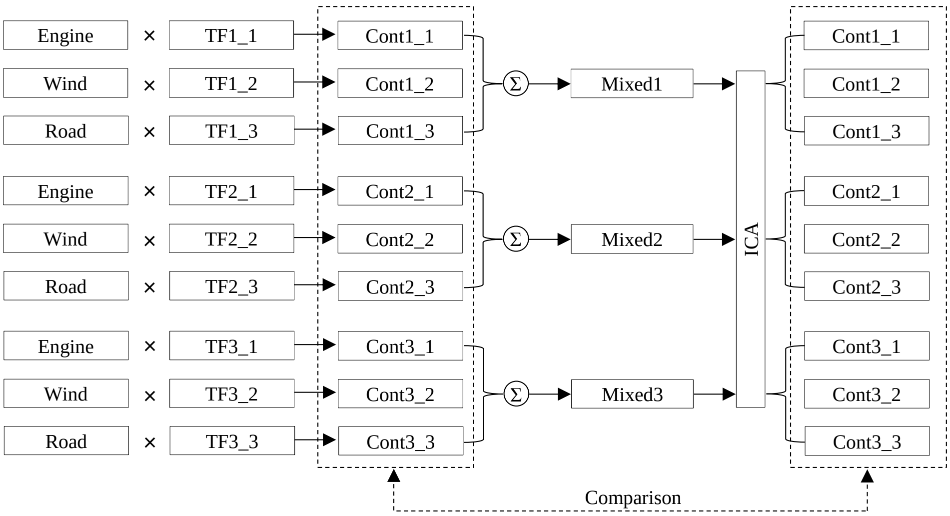
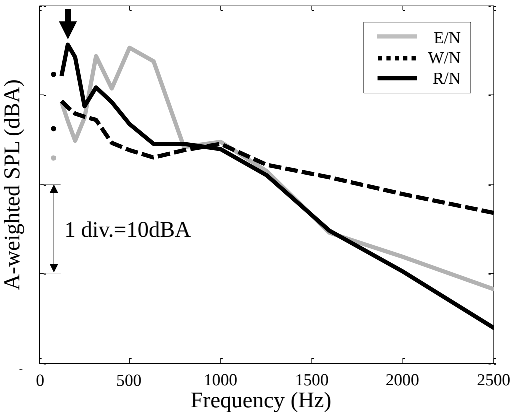


Figure 2 – Evaluation of calculated contribution accuracy

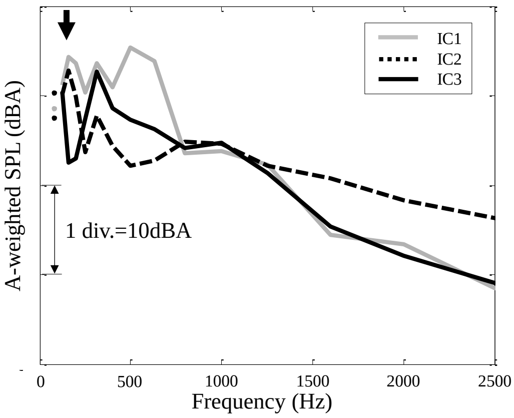
In this figure, “Engine”, “Wind” and “Road” indicate sound sources, and “TF” denotes weighting factors (transfer characteristics). “Cont” in the left indicates the actual contribution obtained by multiplying sound source with transfer characteristics, and “Mixed” indicates mixed signal (simulated interior noise) obtained by adding each contributions. “Cont” in the right denotes calculated contribution by ICA. If the right “Cont” is close to the left “Cont”, it shows the contribution separation result by ICA is accurate.

3.3 Verification result

Figure 3 shows the comparison between actual and calculated contributions in one of the simulated interior noise. Figure 3 (a) shows the actual contributions. Gray solid, black dashed and black solid lines indicate engine, wind and road noise actual contributions, respectively. Figure 3 (b) shows the calculated contributions. Gray solid, black dashed and black solid lines indicate contributions of independent component 1 to 3 (IC1-IC3), respectively.



(a) Actual contribution



(b) Calculated contribution

Figure 3 – Actual and calculated contributions in mixed signal 1

Through these figures, IC1, IC2 and IC3 could be observed to indicate engine, wind and road noise contributions, respectively. However, the sound pressure level (SPL) of the calculated contribution of IC1 at 200 Hz looks like different from the actual engine contribution as shown by arrows in Fig. 3 (a) and (b). In the frequency band, the SPL of engine and road noise contributions (IC1 and IC3) could be observed to switch each other.

These results show ICA could separate the contribution well in general but there were separation errors at a few frequency bands where the correspondence relationship between calculated and actual contributions switched, namely, permutation problem has occurred.

3.4 Solution of permutation problem

Many kinds of solutions for the permutation problem have been proposed until now (10-13). In our previous studies, we proposed some solutions considering characteristics of vehicle sound sources (7, 8). In the method, negentropy of the separated contribution, correlation between the contributions and the size of them have been applied. We tried to solve the permutation problem by referring these solutions as follows.

3.4.1 Permutation solver using negentropy (engine noise extraction)

Engine noise source of a vehicle does not consist of only one sound source in actual, but consists of various transferred sounds such as vibration transferred noise from engine, exhaust noise, intake noise, and so on. Therefore, engine noise source is considered to be composed of various sound sources (sub-sources). As same as engine noise, road and wind noise source have a possibility to consist various sub-sound sources. Hence, non-Gaussianity characteristics of engine, road and wind noises are considered to be different each other depending on the number of actual sub-sound sources of them because distribution of combined signals is known to close to Gaussian distribution according to the number of sound source by the central limit theorem (6). Then, we applied negentropy for evaluating the non-Gaussianity of the sound source to determine which independent component is engine, road or wind noise contribution as same as our previous study (7). Negentropy is obtained by normalizing the differential entropy, and the value is defined as shown in Eq. (3);

$$J(y) = H(v) - H(y) \tag{3}$$

where J (y) is the negentropy of the separated signal, H (v) and H (y) are the differential entropy of stochastic variable and the separated signal, respectively (6). In this study, approximate value as shown in Eq. (4) was used to obtain negentropy (6);

$$J(y) \propto \{\mathrm{E}(\ln\cosh y) - \mathrm{E}(\ln\cosh \nu)\}^2 \tag{4}$$

where E is expectation value.

Figure 4 shows negentropy of each calculated contributions in mixed signal 1.

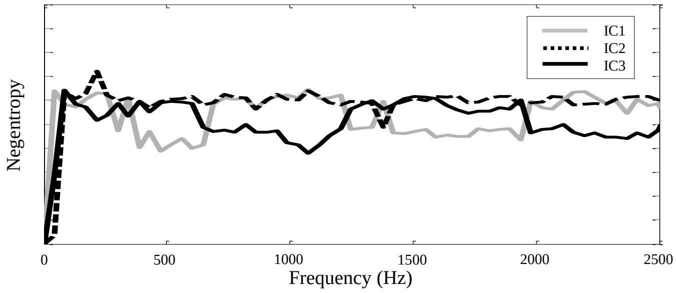
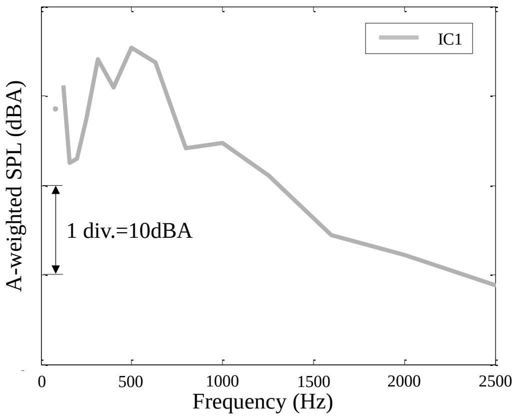
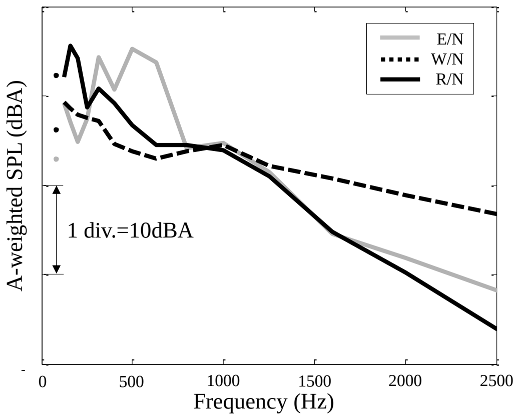


Figure 4 – Negentropy of each calculated contributions in mixed signal 1

Horizontal and vertical axes show the frequency and the calculated negentropy, respectively. Gray solid, black dashed and black solid lines indicate negentropy of IC1-IC3, respectively. From the result, the negentropies are observed to be roughly divided into two groups: large negentropy group including two contributions and small negentropy group including one contribution in each frequency. This means that one of the separated contributions consisted of more sub-sources than the other contributions. Then, we assumed that the calculated contribution having smallest negentropy is the contribution from the same sound source, and transposed the number of the separated contribution to be the contribution having the smallest negentropy as IC1 in each frequency. Figure 5 (a) shows the calculated contribution 1 after transposition of the number using negentropy, and Fig. 5 (b) shows the actual contribution for the comparison.



(a) Calculated contribution (IC1) with permutation solver using negentropy



(b) Actual contribution

Figure 5 – Comparison of calculated contribution 1 and actual contributions in mixed signal 1

As shown in the figure, the IC1 (solid gray line in Fig. 5 (a)) is found to be able to express the engine actual contribution (solid gray line in Fig. 5 (b)) very well and the permutation problem at 200 Hz could be solved by the method.

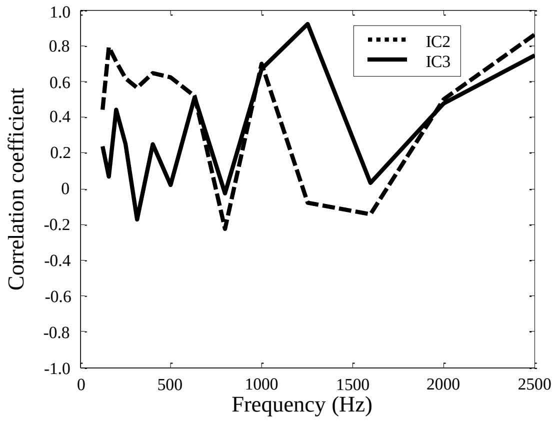
3.4.2 Permutation solver using size and correlation (road and wind noise extraction)

Engine noise contribution could be extracted using negentropy in the previous section but the road and wind noise contributions were difficult to be separated correctly because the difference of negentropy was very small. Consequently, we considered additional permutation solution for separation of wind and road noise contributions using both their sound source characteristics and the correlation among each contribution.

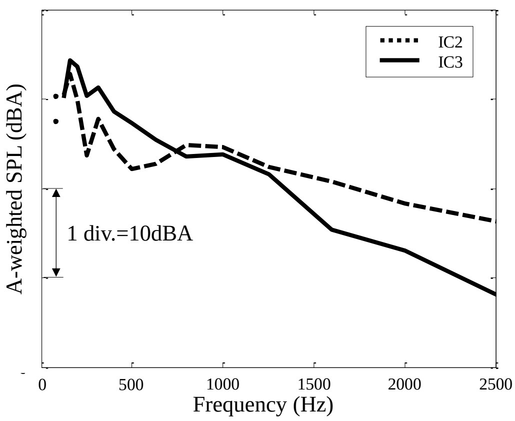
The SPL of wind and road noise contributions are varied along frequency depending on characteristics of the sound source and the acoustical transfer function of the vehicle. However, the SPL of the contribution is unlikely to change largely in close frequency bands by comparing with the engine noise contribution that contribution changes widely depending on engine order sounds and the structural resonances. Hence, as the first step of the permutation solution for road and wind noise contributions, the number of the calculated contributions (IC2 and IC3) except for IC1 (engine contribution) was ranked by the averaged size in each frequency. The larger and smaller contributions are re-named as IC2 and IC3, respectively.

In the second step, the correlation between calculated contribution of IC2 and IC3 were used. The calculated contributions of IC2 and IC3 were ranked according to the size in the first step. At the time, IC2 had higher contribution in all frequency bands; however, there is a possibility to change the number having higher contribution in some frequency bands in actual. In order to find out the frequency where the contribution number exchanges, the correlation coefficient between IC2 and IC3 was calculated in each frequency. For the calculation, IC2 in a frequency was set as the reference signal for calculating correlation and correlation coefficients with IC2 and IC3 in the next frequency were calculated. This procedure was repeated in each frequency and if the correlation coefficient of IC2 and IC3 changed largely (the difference is over 0.2), we assumed where the contributions exchanged, in other words the permutation occurred, and transposes the contribution number. In addition, to evaluate general similarity of contribution fluctuations along the signal recorded period, the correlation coefficient was obtained after a smoothing procedure in which the time fluctuations of contributions in each 0.8 s were calculated in all recorded period of 14 s in each 1/3 octave band.

Figure 6 (a) shows the correlation coefficients of IC2 and IC3 and Fig. 6 (b) shows the obtained contributions of IC2 and IC3 after transposition procedure using both size and correlation described above.



(a) Correlation coefficient



(b) Calculated contribution (IC2, IC3) after transposition

Figure 6 – Correlation coefficients among calculated independent component contributions and calculated contributions after transposition procedure using the size and the correlation

Black dashed and solid lines in Fig. 6 (a) indicate the correlation coefficient of IC2 and IC3, respectively. Black dashed and solid lines in Fig. 6 (b) indicate the calculated contribution of IC2 and IC3 by ICA after transposing procedure using the size and correlation, respectively.

As shown in Fig. 6 (a), the correlation coefficient changes largely under 600 Hz, therefore, we assumed permutation occurred at the frequency band. The number of the calculated contributions were then transposed under 600 Hz to solve the permutation problem.

As the result, as shown in Fig. 6 (b), the contribution of IC3 is found to be larger than the IC2 under 800 Hz and the number of the larger contribution switched over at the frequency. In addition, through the comparison to the actual contributions (Fig. 5 (b)), IC2 (dashed black line in Fig. 6 (b)) and IC3 (solid black line in Fig. 6 (b)) are observed to be able to express the wind noise actual contribution (dashed black line in Fig. 5 (b)) and the road noise actual contribution (solid black line in Fig. 5 (b)) correctly and the permutation problem of road and wind noise could be solved by the method.

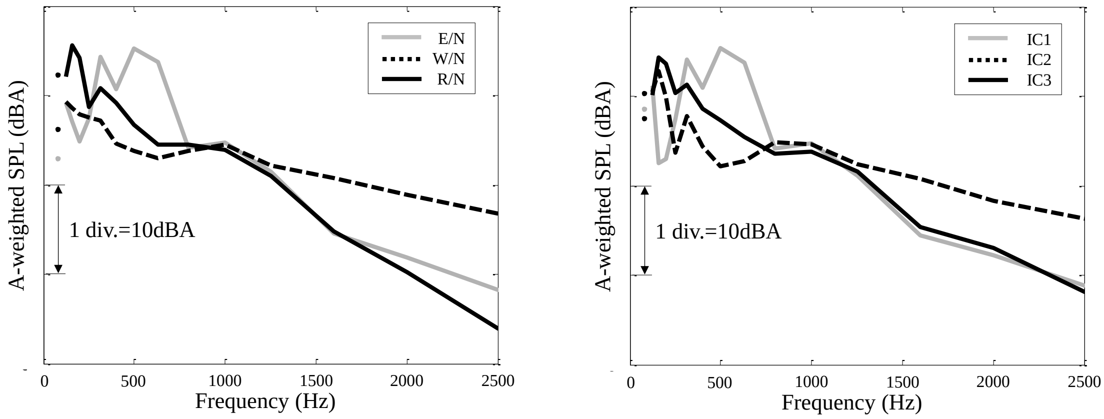
The followings are the outline of the proposed permutation solution;

1. Calculating negentropy of each contribution in each frequency
2. Numbering the contribution having smallest negentropy as IC1 in each frequency (engine noise

extraction)
3. Conversion of the contributions in narrow frequency bands into 1/3 octave bands
4. Smoothing the contributions of IC2 and IC3 along time
5. Calculating the averaged size of each smoothed contributions for the signal duration
6. Re-naming the larger size contribution as IC2 and the smaller size contribution as IC3 in each frequency
7. Calculating correlation coefficients between the reference contribution (IC2) in a frequency and IC2 or IC3 in the following frequency
8. Transposing the contribution number in case the correlation changes largely (over 0.2) (extraction of road and wind noises)

3.4.3 Summary of the permutation solution

Through the above permutation solver for engine, wind and road noise contribution, we attempted to obtain the accurate contribution using only simulated interior sounds. Figure 7 shows the comparison of the actual contributions and the calculated contributions by ICA with three permutation solvers using negentropy, size and correlation.



(a) Actual contribution (b) Calculated contribution

Figure 7 – Actual and calculated contributions in mixed signal 1

Figure 7 (a) shows the actual contributions in mixed signal 1 and Fig. 7 (b) shows the calculated contributions after the transposition procedure. Gray solid, black dashed and black solid lines in Fig. 7 (a) show engine, wind and road noise actual contributions, respectively. Gray solid, black dashed and black solid lines in Fig. 7 (b) show calculated contributions of independent component 1 to 3 (IC1-IC3), respectively.

Through the comparison of these figures, IC1 (solid gray line in Fig. 7 (b)), IC2 (dashed black line in Fig. 7 (b)) and IC3 (solid black line in Fig. 7 (b)) are observed to express engine actual contribution (solid gray line in Fig. 7 (a)), wind actual contribution (dashed black line in Fig. 7 (a)) and road actual contribution (solid black line in Fig. 7 (a)), respectively and the permutation problem could be solved by the proposed transpositions procedure.

Consequently, the ICA method with the solution of the permutation problem could calculate accurate sound source contributions using only response signals.

4. SUMMARY

In this study, we considered an analysis method which can separate contributions of vehicle interior noise using only response signals without any input signals through simple simulation. In the verification of the contribution separation ability using ICA, engine, road and wind noises were employed as the contribution separation targets. Vehicle interior sounds are simulated by mixing these sound sources and contributions were separated using frequency domain ICA method. As the result, the contribution could not be obtained correctly by the permutation problem in which the correspondence relationship between calculated and actual contributions is not kept along frequency. Then, we proposed a solution technique to solve the permutation problem using negentropy of the separated contribution, the average size and the correlation each other. The result showed the calculated contributions could express the actual contributions accurately.

In future, it is necessary to verify the applicability of this method in more complex conditions having various transfer characteristics in addition to consider a method enable us to identify which calculated contribution of independent component indicates actual engine, wind or road noise contribution in order to utilize this method as a convenient analytical tool for vehicle interior noise.

REFERENCES

1. Van der Auweraer H, Wyckaert K, Hendricx W, Van Der Linden P. Noise and Vibration Transfer Path Analysis. Lecture series - von Karman Institute for fluid dynamics. 1979.
2. Bermayer W, Brandl F, Hoeldrich R, Sontacci A, Brandl S, Fliesser W. Sound Engineering based on Source Contributions and Transfer Path Results. JSAE Paper. 2007;318/20075399:7-12.
3. Noumura K, Yoshida J. Method of Transfer Path Analysis for Vehicle Interior Sound with No Excitation Experiment. FISITA2006 Proceedings F2006D183. 2006:1-10.
4. Yoshida J, Noumura K. Noise Reduction Method for Running TPA Using Significance Probability. Journal of System Design and Dynamics. 2011;5(8):1572-1581.
5. Kobayashi S, Yoshimura T. Variance Estimation for the Identified Force Spectra Based on Matrix Inversion Method. Transactions of JSME Series C. 2011;77(776):1342-1355 (In Japanese).
6. Hyvarinen A, Karhunen J, Oja E. Independent Component Analysis. John Wiley & Sons. 2001.
7. Yoshida J, Ishihara H. Method for the Separation of Vehicle Interior Noise Contributions Using Only Response Signals. Journal of System Design and Dynamics. 2013;7(4):416-427.
8. Yoshida J, Hirano T. Basic consideration for contribution separation of vehicle interior noise using independent component analysis (Separation of road and wind noise using only vehicle interior sounds). Transactions of JSME. 2014;80(812):TRANS0063 (In Japanese).
9. Cardoso J-F. BLIND SOURCE SEPARATION and INDEPENDENT COMPONENT ANALYSIS [internet]. [cited 2011 Dec 29]; Available from: http://perso.telecom-paristech.fr/~cardoso/guidesepsou.html.
10. Ikeda S, Murata N. An Approach to Blind Source Separation of Speech Signals. Proceedings of International Conference on Artificial Neural Networks 1998. 1998:761-766.
11. Sawada H, Mukai R, Araki S, Makino S. A Robust and Precise Method for Solving the Permutation Problem of Frequency-Domain Blind Source Separation. IEEE Transaction of Speech and Audio processing. 2004;12(5):530-538.
12. Kurita S, Saruwatari H, Kajita S, Takeda K, Itakura F. Evaluation of blind signal separation method using directivity pattern under reverberant conditions. Proceedings of IEEE Conference on Acoustic, Speech, and Signal Processing 2000. 2000:3140-3143.
13. Di Persia L, Ota K, Yanagida M. A Method for Solving the Permutation Problem in ICA. IEIC Technical Report. 2006;105(686):53-58 (In Japanese).