

Locating Source of Vehicle Pass-by Noise Using Beamforming Method

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ABSTRACT

Aiming at reducing vehicle pass-by noise, attention was focused on an analysis method employing high-directivity remote noise source locating technology (beamforming method). The beamforming method is a measurement method that uses a combination of multi-channel sensor technology and signal processing technology. It features the ability to measure the overall noise source in a short time and also the ability to provide a visual indication of the noise source distribution. A study of the shape, arrangement, and other specifications of the beamforming array for analyzing vehicle pass-by noise was carried out. Based on the results, a noise source locating test was performed using both a dummy noise source and an actual vehicle. As a result (1) a noise source locating instrument that had the required locating accuracy and dynamic range was realized, and (2) it was confirmed by using this instrument to analyze vehicle pass-by noise that this method was effective for reducing noise.

1. Introduction

Demands for reducing road and traffic noise have increased in recent years around the world. Society is urging for the reduction in the sources of the noise, which is primarily pass-by noise from automobiles. There are several direct sources of pass-by noise: the engine, air intake system, exhaust system, and tires. Many components of these sources are responsible for noise and are widely distributed about the vehicle. There often are contradictions between noise control methods and performance. It is essential to begin efficient reductions of noise in the early stages of development of an automobile. Many analytical methods have been attempted for this purpose.

Some representative methods include contribution analysis by masking⁽¹⁾, acoustic intensity⁽²⁾, acoustic holography⁽³⁾, contribution analysis by volume velocity acoustic sources, and the reciprocity principle⁽⁴⁾. Since these methods require much time and labor for the testing and analyses, they can often be inadequate methods from the

standpoint of the limited time given for current short-term development.

Recently, however, there have been some reports describing the beamforming method, a highly directional technology for noise source location at long distances, which has served the fields of aeronautics⁽⁵⁾ and the design of high-speed trains^{(6), (7)}. This method directly observes a noise source using a combination of multi-channel sensor technology and signal processing technology. It enables quick noise source location in a wide target area in a single measurement, using a 2-dimensional array of microphones.

In this study, a noise source location method using the beamforming method was applied to bench analysis of automobile pass-by noise during acceleration. The microphone array most appropriate for pass-by noise analysis was investigated and noise source location was attempted using the resulting array. Based on these results, noise reduction was conducted and it was confirmed that the newly developed method was effective for noise source location.

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2. Theory and Characteristics of the Beamforming Method

2.1. Theory

Beamforming technology is a method of obtaining highly directional (beam) characteristics from a geometric arrangement of sensors on a 2-dimensional plane (a multi-microphone), using signal processing fitted to the geometric arrangement, to obtain data on the distribution of a source within a group of noise sources. The essentials of this method are described below.

Let us assume that acoustic waves approach from a certain direction and M microphones placed in locations r_m ($m = 1, 2, \dots, M$) on an XY plane (Fig. 1). It can be assumed that the signals p_m detected by the microphones have certain delay times Δ_m determined by the direction of approach of the acoustic waves and the position of the microphones. As shown in Fig. 2, by compensating for the delay time of each microphone and summing them, it is possible to highlight the signal coming from a specified direction. “Delay-and-sum beamforming” or just “beamforming” refers to this technique of summation for obtaining highly directional characteristics. The time-base waveform for a specified angle κ is given by the following expression:

$$b(\kappa, t) = \sum_{m=1}^M p_m(t - \Delta_m(\kappa)) \quad (1)$$

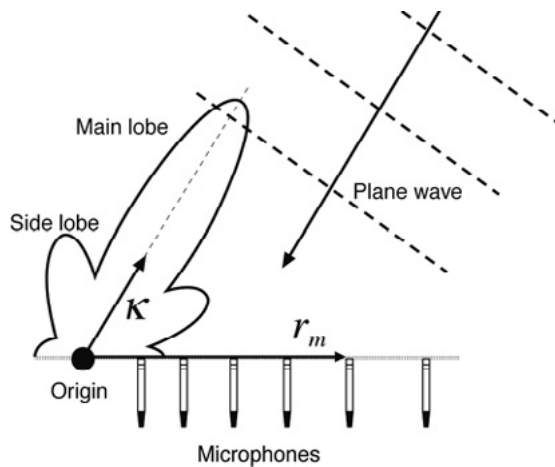


Fig. 1 Beamforming array and directional sensitivity on XY plane

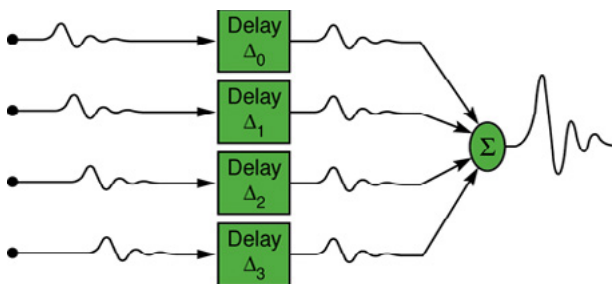


Fig. 2 Principle of beamforming

Since the delay time Δ_m to be applied to each microphone controls the directionality of that microphone, Δ_m is determined as a function of the desired direction represented by the unit vector κ in that direction. The reason for this is to apply the delays to each of the microphone signals representing the planar wave arriving from direction κ coheres the signals before the summing process. The time delay Δ_m is calculated in the following formula, using the position of each microphone array:

$$\Delta_m = \kappa \cdot r_m / c \quad (2)$$

Here, c is the propagation speed of sound. As shown in Fig. 2, the signals arriving from directions other than the chosen direction are not summed in a coherent way but randomly, so that they cancel each other out. As a result, main directionality for the signals from the chosen direction is obtained and called the “main lobe”, while array sensitivity to directionality for the other directions is called the “side lobes”.

2.2. Characteristics

Beamforming technology allows “one-shot” measurements of distant, large objects, even with arrays of rather small diameters. For example, effective measurement results can even be obtained from objects occupying a solid angle of 30° from the central axis of the array.

Ideally, arrays should have no side lobes. In actual use, arrays show “ghost” indications of noise sources in locations where there are no sources due to the side lobes. Design techniques have been developed which attenuate the maximum side lobe levels (effective dynamic range) in the expected frequency range in order to emphasize the relative difference from the main lobe⁽⁸⁾. These techniques were used in this study.

3. Target Setting for Development of Noise Source Location Method

Various methods of analysis of the sources in pass-by noise have been tried, as mentioned above, but many of these require much time and labor for both the tests and the analysis. A beamforming system was constructed as a practical noise source location technology in an attempt to eliminate these issues.

The following targets for our system were set in accordance with the needs of this process of development of an actual automobile:

- (1) The accuracy of noise source location shall be within 25 cm at 1 kHz.
- (2) In order to accomplish this resolution, it shall be possible to detect two 1 kHz sources at a separation of at least 50 cm.
- (3) “One-shot” measurements (a single run per measurement) of the entire vehicle shall be possible.
- (4) Results shall be output within 30 minutes of the total processing time.
- (5) Effective dynamic range of location results shall be more than 10 dB for the analytical frequency region of 400 Hz – 2.5 kHz.

4. Investigation of Microphone Array

Next, an investigation of the following parameters of the microphone array was carried out in preparation for the analysis of noise source location in an entire vehicle: diameter, placement, shapes and number of microphones. The necessary array diameter and placement with respect to the noise source were determined by the desired measurement area and spatial resolution, assuming coverage of an entire vehicle up to 5 m in length and a lower limit of the analytical frequency region of 400 Hz. A semicircular array shape (half-wheel array) was chosen, assuming perfect reflectivity of the floor surface in a measurement environment. This allowed the number of microphones to be cut in half. The number of microphones was set at 42, in consideration of the system structure and the need to obtain adequate spatial position data. The principal specifications of the microphone array are given below and Fig. 3 is a schematic view of the beamforming array.

- (1) Array shape and diameter: semicircular (half-wheel type array), 3 m
- (2) Number of microphones: 42
- (3) Distance between array and noise source: 4 m

5. Verifying Characteristics of Half-wheel Array

In order to verify the performance of the microphone array described in the previous chapter, calculations were carried out to find the resolution, the main performance parameter, and the effective dynamic range, which is determined by maximum side lobe characteristics.

5.1. Capability to Distinguish Noise Sources

The fundamental characteristics of a half-wheel array are determined by its directionality. Therefore, a simulation was carried out in an effort to predict how well the method would distinguish between two noise sources.

Figure 4 is a contour map showing the results of a calculation carried out for the indicated distribution of noise sources as analyzed by this array resulting from two 1 kHz sources at the desired spacing of 0.5 m. These results show that the observed separation would be slight, but that the array would be able to distinguish two sources.

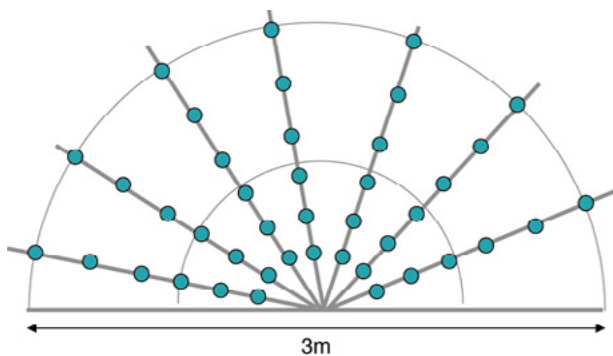


Fig. 3 Typical half-wheel array (42 microphones)

5.2. Maximum Side Lobe Characteristics

As described earlier in Section 2, the spatial arrangement of the microphone array determines its directionality. Directionality means a sharp beam shape for the main lobe in the direction of the main axis of the array; it is, therefore, desired that the sensitivity of the side lobes to other directions be kept well below (at least 10 dB below) that of the main lobe. If side lobe sensitivity is insufficiently suppressed, ghost images will appear in the acoustic diagram, making it a challenge to accurately determine the location of the noise source in practical use. Since the location of each microphone in the array is affected by the wavelength, the difference in levels between the sensitivities of the main lobe and the maximum side lobe (the effective dynamic range) can be expressed as a function of frequency. The effective dynamic range of this half-wheel array is shown in Fig. 5. These results indicate that the desired 10 dB effective dynamic range was attained in the effective region of 400 Hz – 2.5 kHz.

6. Measurement Accuracy in This Method with Dummy Noise Source

An actual 42-channel microphone array was built and a test was carried out with a dummy noise source of a loud speaker to verify the basic performance of the method.

6.1. Accuracy of Single Noise Source Location

The position error was investigated in a dummy noise source test of the beamforming array in order to study the error of the array in identifying the location of the real

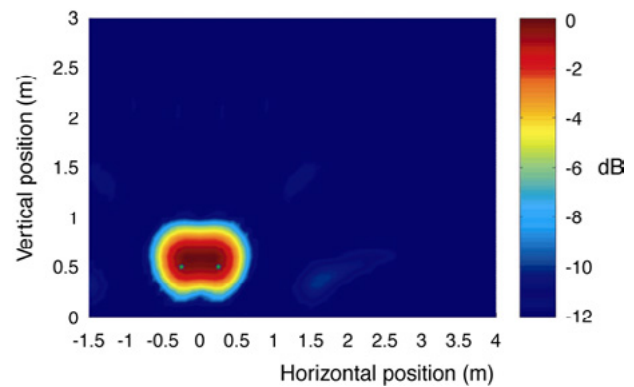


Fig. 4 Result of simulation (42 microphones)

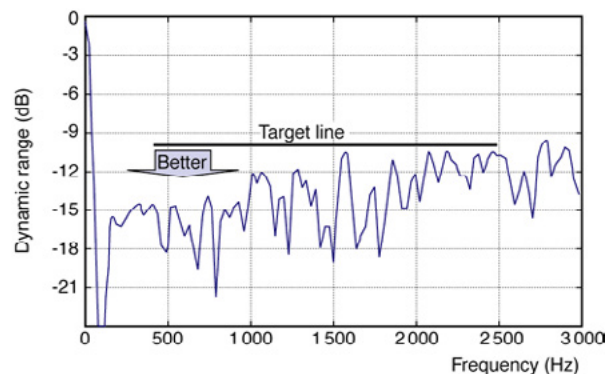


Fig. 5 Maximum side lobe response (42 microphones)

source. Figure 6 provides some typical results. The source was placed at a height of 5 cm above the floor in a semi-anechoic room and the noise signals generate 1 kHz pink noise. The distance between the noise source and the microphone array was 4 m. The results are shown as a noise contour map with a center frequency of 1 kHz 1/3-octave band. The region for which calculations were carried out measured 5 m wide x 2.5 m high. These results indicate that the accuracy of location of noise sources was within the target of 25 cm. Also, the contour map is marked in 10 dB ranges relative to the maximum noise level, but there were no ghost images. It was thus verified that the dynamic range of 10 dB had been realized.

6.2. Capability to Distinguish Two Noise Sources

Next, the sound field from two loud speaker noise sources (1 kHz band passed uncorrelated pink noise signals) 50 cm apart was observed with the beamforming array to verify the system's ability to resolve separate sources. The distance between the noise source and the microphone array was 4 m. The resulting noise contour map with a center frequency of 1 kHz 1/3-octave band is presented in Fig. 7. These show that distinct 1 kHz sources separated by the target distance of 50 cm were successfully distinguished by the system.

6.3. Verifying Transient Phenomena Performance

It is necessary to be able to carry out a noise source location analysis on an accelerating automobile, whose engine is operating at an arbitrary speed. For this purpose, the analytical method must be applicable to transient as well as

to stationary phenomena; this can impose discrepancies in results for measurements of stationary phenomena. The discrepancies were investigated by using two speaker dummy noise sources, in supplying a stationary signal, and a transient signal.

The results under stationary sources are provided in Fig. 8 in a noise contour map with a center frequency of 1 kHz 1/3-octave band. Both loud speakers were emitting 1 kHz uncorrelated pink noise; source-microphone array distance was 2 m.

Figure 9 shows the results under a transient 2-source signal in the form of a noise contour map with a center frequency of 1 kHz 1/3-octave band. The noise signals were set to generate in frequency from 100 Hz to 5.1 kHz in 5 sec; a higher speed than will occur in noise frequency from accelerating vehicle engines. The analysis was carried out for the transient 1 kHz signal during that process. The distance between the noise source and the array and the location of the speakers were the same as in the stationary tests. The results obtained in this test, shown in Figs. 8 and 9, were similar to those in the stationary tests. It was verified that this system would provide valid results for transient phenomena.

7. Application of System in Bench Analyses

An example of application of the system proposed in this paper to measurements of an actual vehicle is given here.

A vehicle with a 1.5L in-line 4-cylinder engine and automatic transmission was used.

The vehicle was placed on a chassis dynamo in a semi-



Fig. 6 Result of single source test (loudspeaker, 1 kHz)

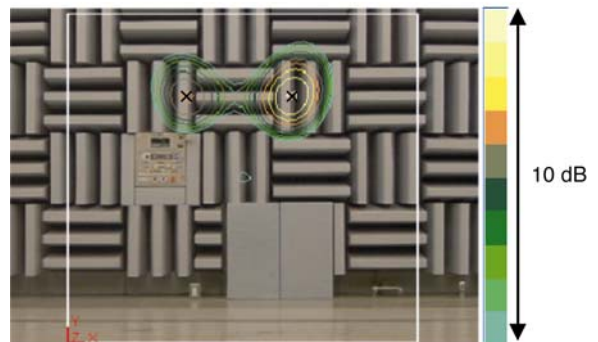


Fig. 8 Result of stationary tone test
(x: Noise source)

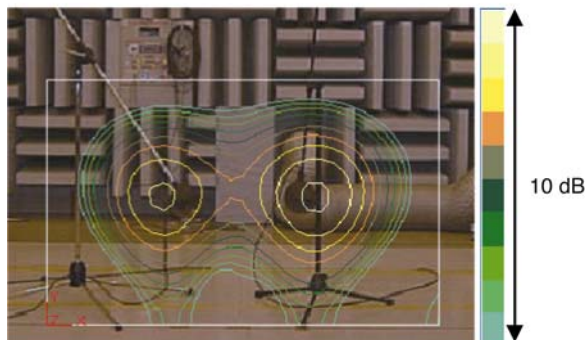


Fig. 7 Result of two-source test (loudspeaker, 1 kHz)

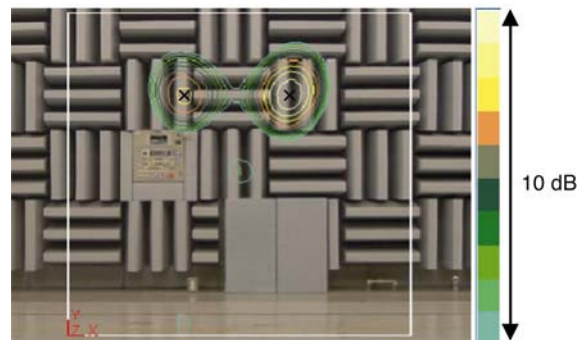


Fig. 9 Result of sweep tone test
(x: Noise source)

anechoic room and the dynamo was operated to enact a driving test with a controlled rolling resistance, simulating real driving conditions. The microphone array used for the analysis was arranged 4 m from the side of the vehicle, so that a single test could be performed; simultaneously, a single microphone was placed 7.5 m from the center of the vehicle at a height of 1.2 m to evaluate a far field (Fig. 10). The engine speed was reported by a sensor and recorded as well as the signals from the microphones by the analytical system.

The vehicle was accelerated at full power from an initial speed of 50 km/h during the same drive range as a driving mode specified in ISO 362 acceleration test, and time signal recording was done for about 1.5 sec as the vehicle passed through the measurement area (over 20 m long).

The analysis of the noise source location results and evaluation point results was conducted on the time signal at the engine speed at which the acceleration noise was the maximum (3 600 rpm).

Figure 11 shows the frequency spectrum observed from the original vehicle at the evaluation point. The frequency component showing the maximal level was 1 184 Hz, so this frequency was examined more closely. A noise source location analysis was also performed at 1 184 Hz on the microphone array signal, which had been taken at the same time; the results are shown in Fig. 12. These indicated that the main noise sources were the rear side of the front tires.

On the basis of these results, the test was re-performed after sound barriers had been installed behind the front tires. Figure 13 shows the results of the analysis performed at the same frequency as before. It is clear that the noise radiated by the main source component had been attenuated. Figure 14 presents a comparison of the analytical results for the frequency response, taken at the evaluation point at the same

time, with the original frequency spectrum. This confirmed a roughly 12 dB reduction in noise at the target frequency, 1 184 Hz.

Next, the vehicle condition was changed and the exhaust noise radiated from the rear part of the exhaust system was recorded during the same driving range. The frequency analysis results at the evaluation point in this experiment are shown in Fig. 15. Prominent peaks in the spectrum are seen at 1 760 Hz and 1 880 Hz. These frequencies were chosen for closer examination. Figure 16 displays the noise source location results at these frequencies; it is clear that the source of this radiated noise was the rear part of the exhaust system.

The results of noise source location without the exhaust noise radiation and a comparison of the spectrums at the evaluation point with and without the exhaust noise radiation, are given in Figs. 17 and 18, respectively. There was a correlation between the noise source location results and the sound pressure level in the evaluation point. Thus, these analytical results for the vehicle showed that the location results are effective when the sound pressure level at evaluation points is reduced. Also, the time necessary for this task, from the measurement to the noise source location analysis, was within the target of 30 min.

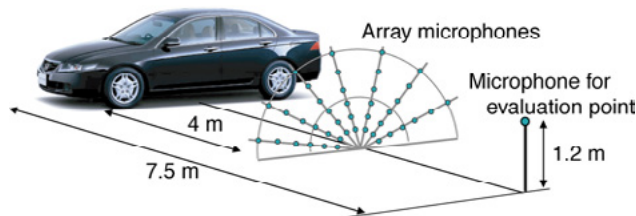


Fig. 10 Measurement condition



Fig. 12 Result of beamforming analysis

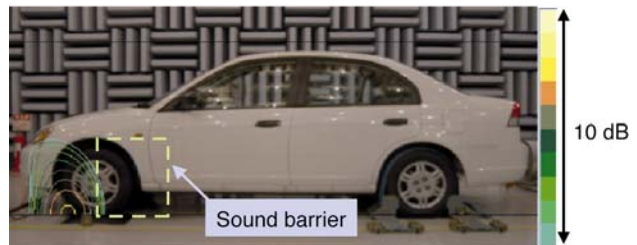


Fig. 13 Result of beamforming analysis (with sound barrier)

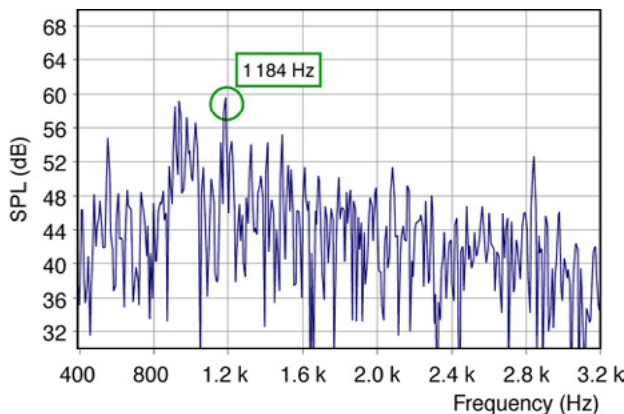


Fig. 11 Sound pressure spectrum at evaluation point

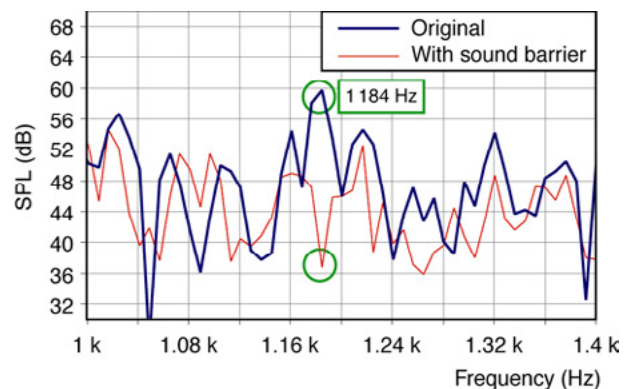


Fig. 14 Sound pressure spectrums at evaluation point

8. Conclusion

This paper reports the results of the application of the beamforming method of noise source location, which is one way for performing bench analysis of vehicle pass-by noise. A microphone array appropriate for analysis of pass-by noise

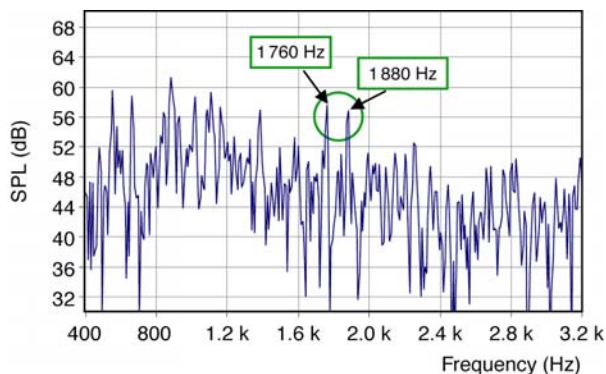


Fig. 15 Sound pressure spectrum at evaluation point



Fig. 16 Result of beamforming analysis (with exhaust noise radiation)



Fig. 17 Result of beamforming (without exhaust noise radiation)

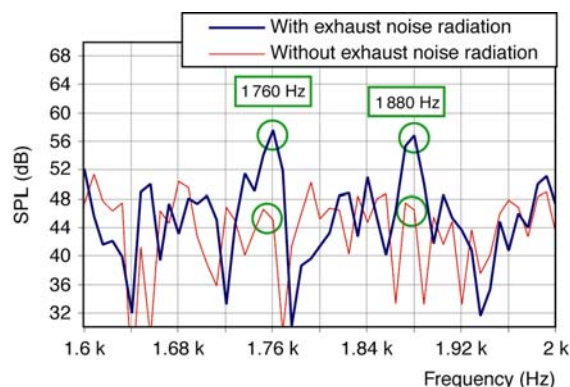


Fig. 18 Sound pressure spectra at evaluation point

was investigated as part of this effort. Tests of noise source location were carried out to examine the effectiveness of both the loud speakers and the vehicle noise source identification. As a result:

- (1) A beamforming system incorporating a microphone array was created which met the targets for accuracy of noise source location, one-shot measurements, adequate processing time and effective dynamic range.
- (2) It was confirmed that this method is effective for reducing noise by its application for noise source analysis of pass-by noise.

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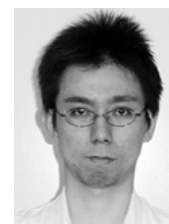
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