

NUMERICAL STUDY OF ACTIVE NOISE BARRIER BASED ON THE BOUNDARY SURFACE CONTROL PRINCIPLE

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1. INTRODUCTION

In many situations, undesired noise is radiated into the far field. If the noise source is fixed and well defined, it is possible to suppress the radiation scattered by the primary noise source by surrounding the noise source with the layer of secondary sources. An alternative is to use secondary sources spaced on a square grid to absorb normally incident noise. This concept is known as an active noise barrier (ANB).

In recent years, the effectiveness of the ANB has been confirmed experimentally ^{[1][2]}. However, in the same way as with other applications of active noise control (ANC), the practical implementation of the ANB has its difficulties. In conventional studies of the ANB, the system has been focused on point control at an edge of a barrier or at a point around a barrier. Although this system is effective at the error sensor point, effectiveness in the area to be made quiet cannot be expected. This means that it is not possible to calculate the cost of the ANB that satisfies a client's requirements. In order to overcome these difficulties, it is necessary to construct a design method for the ANB that enables us to judge the scale of both the barrier and the ANC system. In this paper, we propose a design method for the ANB based on the boundary surface control (BSC) principle that can generalize the specification of the ANB. Further, the fundamental principle of this method is discussed by numerical analysis based on the two-dimensional boundary element method (BEM).

2. ACTIVE NOISE CONTROL BASED ON THE BSC PRINCIPLE

Consider a volume V enclosed by a boundary surface S that does not contain a sound source within the volume (Fig.1). The Helmholtz equation related to acoustic pressure given by $(\nabla^2+k^2)p(\mathbf{r})=0$ can be written by the Helmholtz-Kirchhoff integral equation as,

$$\iint_S -j\omega\rho_0 v_n(\mathbf{r})G(\mathbf{r}|\mathbf{s}) - p(\mathbf{r})\frac{\partial G(\mathbf{r}|\mathbf{s})}{\partial n}\delta S = \begin{cases} p(\mathbf{s}) & \mathbf{s} \in V \\ 0 & \mathbf{s} \notin V \end{cases} \quad (1)$$

where \mathbf{n} is the unit normal vector pointing outwards from the closed surface S . $v_n(\mathbf{r})$ is the particle velocity in the n direction, and has the following relationships with the pressure.

$$v_n(\mathbf{r}) = -\frac{1}{j\omega\rho_0} \frac{\partial p(\mathbf{r})}{\partial n} \quad (2)$$

$G(\mathbf{r}|\mathbf{s})$ is the Green function, which is expressed as,

$$G(\mathbf{r}|\mathbf{s}) = -j\frac{1}{4}H_0^{(2)}(k|\mathbf{r}-\mathbf{s}|) \quad (3)$$

in the two-dimensional sound field.

If we assume the surface S in Eq. (1) to be divided into N areas S_i ($i=1\cdots N$), and the pressure $p(\mathbf{r})$ and particle velocity $v_n(\mathbf{r})$ as uniform inside S_i , Eq. (1) can be approximated by

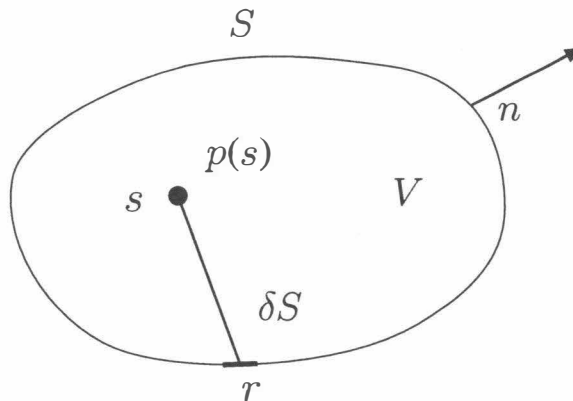


Fig.1 Volume V enclosed by a boundary surface S .

$$\sum_{i=1}^N [g_n(\mathbf{r}_i|\mathbf{s})p(\mathbf{r}_i) + g(\mathbf{r}_i|\mathbf{s})v_n(\mathbf{r}_i)] = \begin{cases} p(\mathbf{s}) & \mathbf{s} \in V \\ 0 & \mathbf{s} \notin V \end{cases}, \quad (4)$$

where,

$$\begin{aligned} g(\mathbf{r}_i|\mathbf{s}) &= -j\omega\rho_0 \iint_{S_i} G(\mathbf{r}|\mathbf{s})\delta S, \\ g_n(\mathbf{r}_i|\mathbf{s}) &= - \iint_{S_i} \frac{\partial G(\mathbf{r}|\mathbf{s})}{\partial n} \delta S. \end{aligned} \quad (5)$$

In Eq. (4), $g(\mathbf{r}_i|\mathbf{s})$ and $g_n(\mathbf{r}_i|\mathbf{s})$ are constants determined by the relative location of each boundary element. Therefore, if the pressure $p(\mathbf{r}_i)$ and the particle velocity $v_n(\mathbf{r}_i)$ are zero, Eq. (4) implies that the pressure $p(\mathbf{s})$ becomes zero at all points of the volume V . Eq. (4) is expressed as

$$\begin{aligned} \forall \mathbf{r}_i \in S \quad p(\mathbf{r}_i) = 0, \quad v_n(\mathbf{r}_i) = 0 \\ \implies \forall \mathbf{s} \in V \quad p(\mathbf{s}) = 0. \end{aligned} \quad (6)$$

Eq. (6) suggests from the BSC principle that if the pressure and the particle velocity of all control points on the surface S are controlled to zero, it is possible to set a pressure level in all positions within a volume V to zero [3].

3. APPLICATION OF BOUNDARY SURFACE CONTROL TO BARRIER

If the principle of BSC is adopted, the flow of acoustic energy can be reflected on a boundary surface where the sound pressure and particle velocity are controlled [5]. In addition, increasing the number of secondary sources will improve the control effect. Therefore, the degree of improvement can be forecast from the number of secondary sources in the same way as for a passive barrier.

3.1 Configurations of active noise barriers

An ANB will have one of the configurations (b), (c) or (d) in Fig. 2. This paper discusses the ANBs (b) and (c) in Fig. 2. The barrier of Fig. 2 (a) is referred to as a passive barrier.

An ANB is equipped with energy sensors which sense both pressure and particle velocity

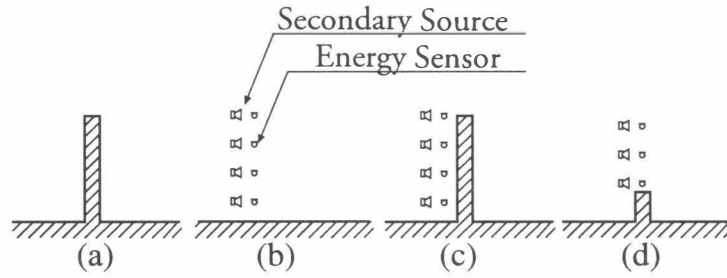


Fig.2 Model of active noise barrier. (a) passive noise barrier, (b) active noise barrier, (c)(d) combination of active noise barrier and passive barrier.

and secondary sources. The amplitudes of the secondary sources are set to minimize the acoustic energy at the sensor positions. Therefore, an ANB reflects acoustic energy from noise at the sensor positions. In actual systems, the pressure and the particle velocity should be measured at discrete positions on the surface because they cannot be detected at every position.

The discreteness may be great at a low frequencies but should be small at high frequencies. Therefore, even when the barrier size is the same, more sensors are required for higher frequencies. As a large number of sensors makes it necessary to maintain the control effect at more positions, the number of secondary sources should be increased at the same time.

3.2 Determination of the amplitudes of secondary sources

When there are N noise sources of amplitude A'_n at position \mathbf{s}'_n ($n = 1$ to N) and M secondary sources of amplitude A'_m at position \mathbf{s}'_m ($m = 1$ to M), the sound pressure and particle velocity at position \mathbf{r} can be expressed as follows:

$$p(\mathbf{r}) = \sum_{n=1}^N A'_n H_p(\mathbf{s}'_n | \mathbf{r}) + \sum_{m=1}^M A'_m H_p(\mathbf{s}'_m | \mathbf{r}), \quad (7)$$

$$\mathbf{v}(\mathbf{r}) = \sum_{n=1}^N A'_n \mathbf{H}_v(\mathbf{s}'_n | \mathbf{r}) + \sum_{m=1}^M A'_m \mathbf{H}_v(\mathbf{s}'_m | \mathbf{r}), \quad (8)$$

where, $H_p(\mathbf{s} | \mathbf{r})$ and $\mathbf{H}_v(\mathbf{s} | \mathbf{r})$ are the transfer functions related to the pressure and the particle velocity between \mathbf{s} and \mathbf{r} . These transfer functions are calculated by BEM. Boundary S of the object control area is made discrete for K with the central coordinate of the boundary element as \mathbf{r}_k and the unit normal vector as \mathbf{n}_k ($k = 1 \cdots K$). Error judgment J_e is defined as follows:

$$J_e = \frac{\rho_0}{2} \sum_{k=1}^K \left[\frac{|p(\mathbf{r}_k)|^2}{\rho_0^2 c^2} + |\mathbf{v}(\mathbf{r}_k) \cdot \mathbf{n}_k|^2 \right] \quad (9)$$

J_e is an equivalent to the acoustic energy on boundary S . To obtain the amplitude of the secondary source that makes J_e small, solve the following equation for A_m by applying Eq. (7), Eq. (8) and Eq. (9):

$$\frac{\partial J_e}{\partial A_m} = 0 \quad m = 1 \dots M \quad (10)$$

4. NUMERICAL CALCULATION

4.1 Calculation model

To check this technique with regard to the feasibility of its principle, numerical calculations were made using the two-dimensional BEM. The primary and secondary sources and sensors were arranged in the two-dimensional sound field shown in Fig. 3. The passive barrier position was defined as the X-coordinate origin and the ground as the Y-coordinate origin. The primary source was installed 7.5 meters in front of the passive barrier, and the secondary source and sensor were installed 1 and 0.5 meters in front of the passive barrier, respectively. The ground and barrier are assumed perfectly rigid. Therefore, "method of images" were used for the numeric calculations. The input signal of the secondary source was determined to minimize the acoustic energy at the sensor position and the sound pressure level was then calculated. The element dimension of the

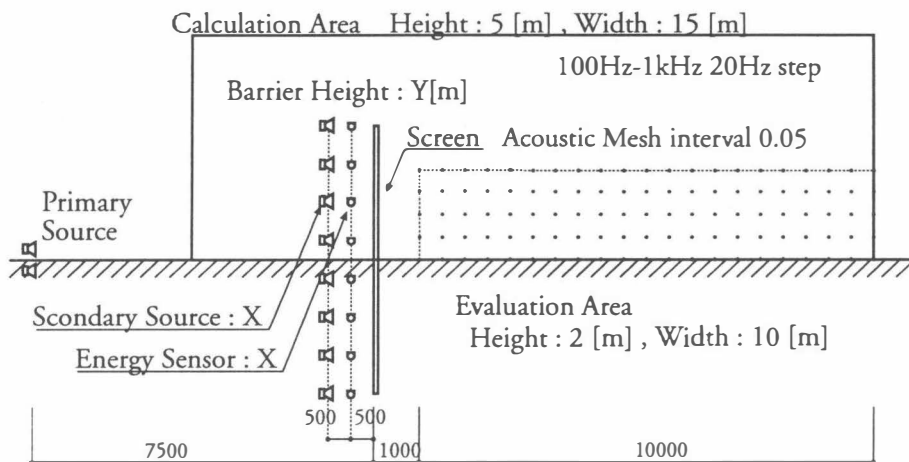


Fig.3 Two-dimensional model of numerical calculation.

passive barrier was set to 5 cm to satisfy the accuracy requirements at the calculation frequencies. The calculation area was set to 5 meters high and 15 meters wide. The sound pressure level was calculated every 20 Hz in the range from 10 Hz to 1 kHz.

4.2 Calculation conditions

The sound pressure level was measured with 2, 4, 8, and 16 sensors attached at heights of 1, 2, and 3 meters to the active and passive noise barriers (see (b) and (c) in Fig.2). The height of the passive barrier and the height of the sensor are the same. The condition name format is “X + number of sensors (secondary sources) + top sensor height + passive barrier height.” X16Y30 means that the number of sensors is 16, the top sensor height is 3 m, and the passive barrier height is 0 meters (in other words, no barrier). The same number of sensors as secondary sources should be installed on the X-coordinate axis at equal height intervals. To make all the calculation intervals equal, the first sensor from the ground was installed with half the interval for other sensors.

4.3 Calculation results

4.3.1 Sound pressure distribution contour

As an example of calculation results, Fig. 4 shows the sound pressure distribution of the control effect at 500 Hz. The barrier height was set to 3 meters and the number of sensors (secondary sources) was set to 16 for Fig. 4 (a) and (b), 8 for Fig. 4 (c) and (d), and 4 for Fig. 4 (e) and (f). For

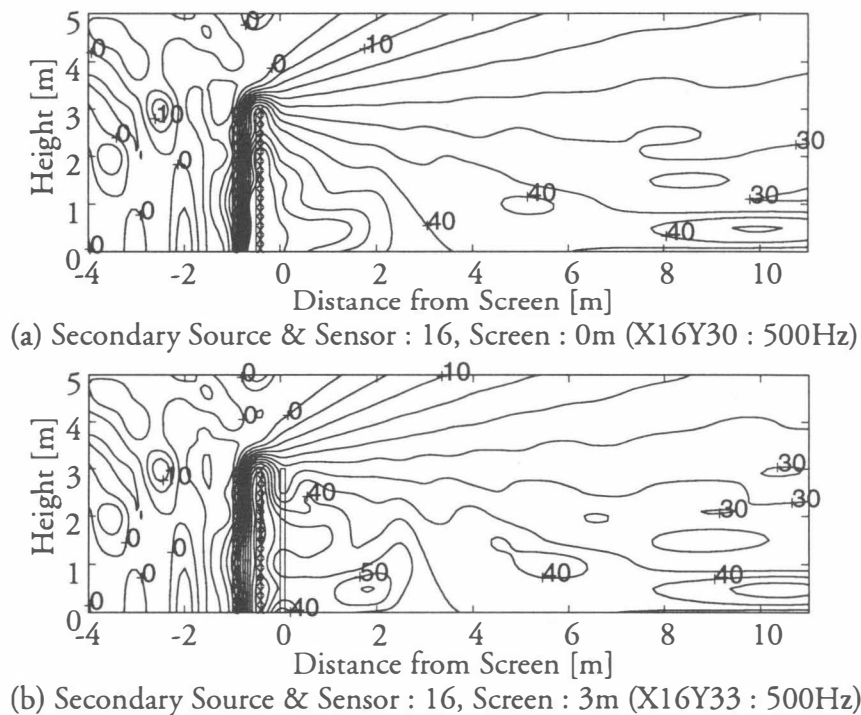
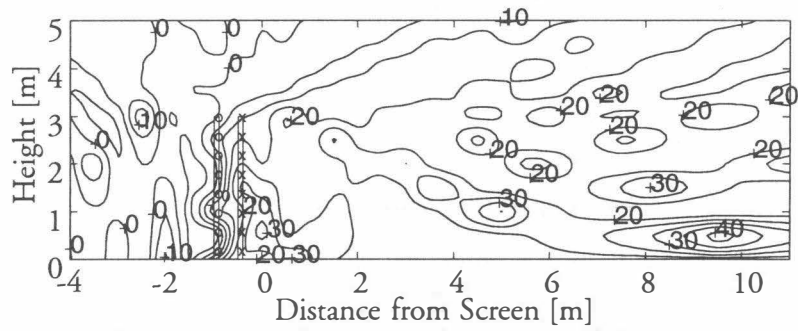
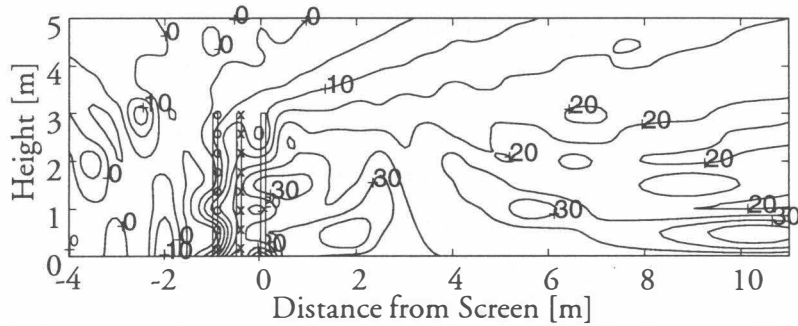


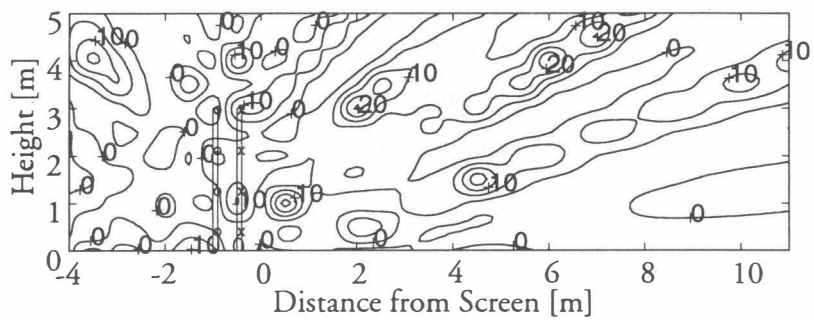
Fig.4 (a)-(b) Sound pressure distribution contour of the control effect at 500 Hz.



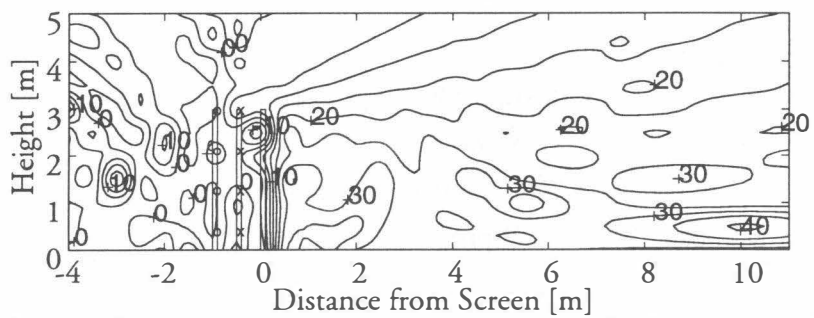
(c) Secondary Source & Sensor : 8, Screen 0m (X8Y30 : 500Hz)



(d) Secondary Source & Sensor : 8, Screen : 3m (X8Y33 : 500Hz)



(e) Secondary Source & Sensor : 4, Screen : 0m (X4Y30 : 500Hz)



(f) Secondary Source & Sensor : 4, Screen : 3m (X4Y33 : 500Hz)

Fig.4 (c)-(f) Sound pressure distribution contour of the control effect at 500 Hz.

Fig. 4(b), (d), and (f), a passive barrier was used under the conditions of Fig. 4 (a), (c), and (e), respectively. In the figure, [O] indicates a secondary source position and [X] indicates a sensor position. In Fig. 4 (a) and (b), use of a barrier does not produce any improvement effect, however, use of a barrier produces an improvement the control effect indicated in Fig. 4 (d) compared to that indicated in Fig. 4 (c). Compared to Fig. 4 (c), the control effect is greater in Fig. 4 (a) where more sensors are used. This is because 8 control points are not enough for sound field control. This tendency is more obvious in Fig. 4 (e) and (f). While the ANB shows almost no effect in Fig. 4 (e), the passive barrier apparently attenuates sound in Fig. 4 (f).

4.3.2 Intensity flow

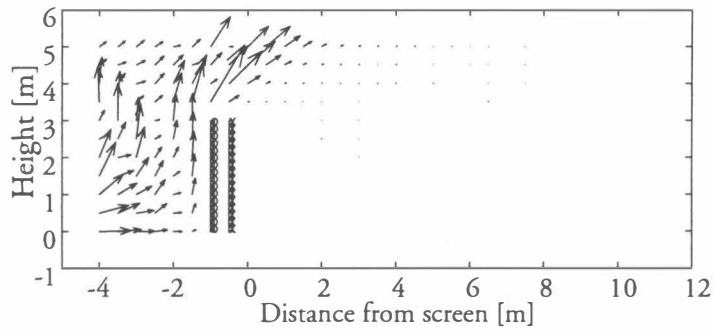
Fig. 5 shows intensity flows to confirm that an ANB reflects acoustic energy flow by noise at a sensor position.

Fig. 5 (a) shows intensity flow with 16 control points when an ANB is used with sensors placed at a height of 3 m. Fig. 5 (b) shows the intensity flow at 500 Hz when only a passive noise barrier at a height of 3 m is used. As in Fig. 5 (b), the intensity flow in Fig. 5 (a) is reflected at the barrier position toward the upper right of the figure.

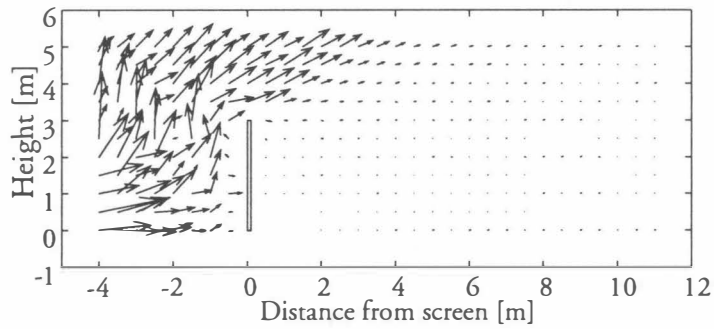
The number of control points in Fig. 5 (c) and (d) is 4, fewer than in Fig. 5 (a). Fig. 5 (c) shows the intensity flow at 400 Hz and Fig. 5 (d) shows the intensity flow at 600 Hz. As in Fig. 5 (a), the acoustic energy flow in Fig. 5 (c) is reflected, however, in the case of in Fig. 5 (d) when an ANB is used, the acoustic energy passes through the barrier and it has no effect. The sensor pitch is 57 cm in both Fig. 5 (c) and (d) but the calculated wavelength is 85 cm in Fig. 5 (c) and 57 cm in Fig. 5 (d). To reflect the intensity flow, the sensor pitch should be smaller than the wavelength of a sound to be controlled.

5. CONCLUSIONS

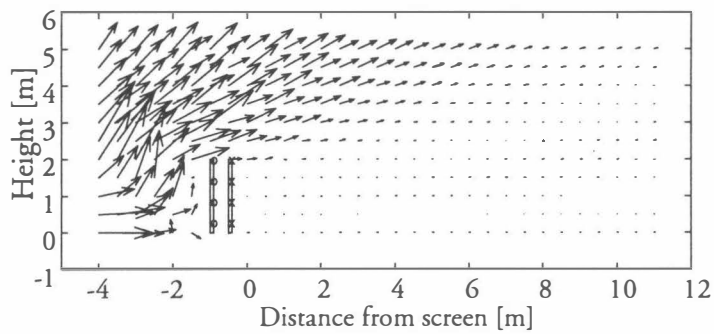
If an ANB is used according to the design rules explained in this paper, its performance can be designed independently to that of a passive noise barrier. To increase the noise reduction effect, the sensor pitch should be reduced. For ANC control, the sensor pitch should be smaller than half the wavelength of the target noise. If the ANB produces a control effect, the noise level can be reduced by 10 dB or more compared to the case of a passive barrier alone. Even when the noise frequency is low and the sensor pitch is reduced to decrease the number of sensors, using a passive barrier together with an ANB ensures a sound insulation effect (by the conventional passive barrier) even at high frequencies where no control effect can be expected. Lastly, if the restrictions on installation area are eased, it is preferable to extend the interval between secondary source and error sensor and to place the sound sources along the wave front created by the primary source.



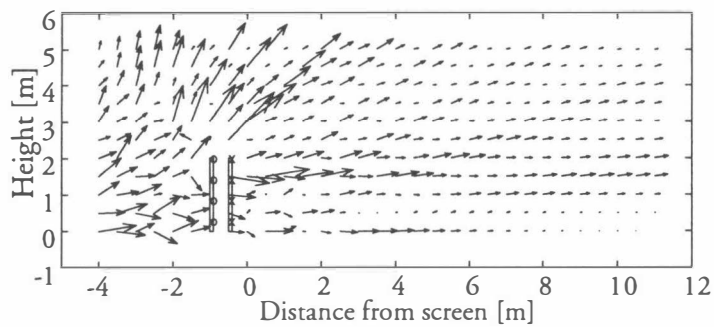
(a) Secondary Source & Sensor : 16, Screen : 0m (X16Y30 500 Hz)



(b) Secondary Source & Sensor : 0, Screen : 3m (X0Y03 500 Hz)



(c) Secondary Source & Sensor : 4, Screen : 0m (X4Y20 400 Hz)



(d) Secondary Source & Sensor : 4, Screen : 0m (X4Y20 600 Hz)

Fig.5 Intensity flow of barrier

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