비균질한 천해에서의 수중음파 전파

Underwater Sound Propagation in a range-dependent Shallow water environment

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요 약

비균질한 천해에서의 저주파 수중음파의 전파 특성을 수치모델을 이용 분석하였다. 특히 전파매질의 비균질성이 독특한 대한해협의 겨울철 해수특성을 고려하여 음속의 수평변화, 저질두께 및 감쇠계수의 변화, 수심의 변화등 천해의 독특한 환경 변화요인을 거의 망라한 경우를 모델로 삼았다. 음원과 수신기의 수심을 수면가까이에 둔 경우 소위Mode function의 수심에 따른 특성에 의한 손실이 일반적인 손실원인보다 크게 나타났으며 Adiabatic approximation을 이용한 Mode coupling효과는 High Mode의 감쇠특성에 의해 천해에서의 모델 적용 가능성을 보여주었다.

ABSTRACT

Low frequency sound propagation in a range-dependent shallow water environment of the Korea Strait has been studied by using the adiabatic coupled mode model, ADIAB. The range-dependent environment is unique in terms of horizontal variations of sound velocity profiles, sediment thickness and attenuation coefficients and water depths. For shallow source and receiver depths, the most important mechanism involved in the propagation loss is the depth changing character of mode functions that strongly depends on the local sound velocity profile. Application of the adiabatic coupled mode theory to shallow water environment is reasonable when higher modes are attenuated due to bottom interaction effects.

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Underwater sound propagation in a range-dependent shallow-water environment

I. INTRODUCTION

In a horizontally stratified medium, the varations in the properties of the waveguide are restricted to the vertical direction. The types of variations of the medium encountered in the ocean are depth changing sound speed and density. On the other hand the range dependence in the ocean is always present, though it is in general much weaker than the depth dependence. The range dependence of the medium in shallow-water environment can be described in two ways. One is the horizontal variations of sound speed profiles and the other is the horizontal variations of the boundary conditions in terms of the depth variations as well as the underlying sediment distributions. The aforementioned conditions of range dependence do not always exist in the most shallow-water environment, however, seasonal changes in the water mass characteristics can be expected in some local area, where tides and cold winds mix the vertical column of shallower water more rapidly than the deeper water to produce changes in the horizontal sound velocity profiles. Moreover when these changes occur over the sloping bottom of horizontally varying sediment compositions, the range dependent effects on the sound propagation will be dominant.

The types of methods for modeling sound propagation in a range dependent medium are the same as for a horizontally invariant medium and may be classified as ray theoretical or wave theoretical(1). The ray theory approach to the description of sound propagation is based on a WKB(1.2.3) asymptotic solution of the acoustic wave equation, and is valid only in the limit of high frequencies. The wave theory approach to the modeling of sound propagation in a range dependent medium is an exact treatment of the problem in formulation and valid for all frequencies. Most applications of wave theory, however, are to low frequency sound propagation because the numerical sampling of the medium, which is wavelength dependent, becomes so fine at high frequencies that a numerical solution is not practical. There are three wave theoretical methods for description of sound propagation. One is a full three-dimensional numerical solution of the wave equation. Another is parabolic equation method, which has been wide use in the underwater acoustics modeling. The final one is the coupled mode theory. The later two methods have been applied to acoustic wave propagation. In the parabolic equation method(4,5), the Helmholtz equation for the acoustic field is approximated by a differential equation which is parabolic in form, and the feild so obtained is not valid at ranges near the source and also suffers from some serious disadvantages concerning the description of the bottom.

The coupled mode theory was proposed for use in underwater acoustic propagation applications by Pierce(6) and Milder(7). It was shown that one may still employ mode theory in an approximate fashion by performing an "adiabatic" separation of the depth and range coordinates in the wave equation. Within the adiabatic approximation, which is expected to be valid for weakly range dependent media, the mode-mode coupling effects are ignored (8, 9). Most applications of the theory have involved the range dependent propagation media that includes the range dependence of the water-sediment interface(10), the wedge-shaped isovelocity ocean(8) and the sloping bottom with sediment attenuation effects(11). Especially the study of slope propagation dependence on several bottom type(11) based on the adiabatic normal mode model reveals several factors that are the basic mechanisms of acoustic slope progagation. They are spreading loss, renormalization loss, bottom attenuation and differential mode excitation.

As stated, in some local area like shallow water environment around the Korea strait, winter time mixing of whole water colum reveals almost horizontal dependent sound velocity profiles over the sloping bottom of different sediment compositions across the strait(See Table 1).

Therefore, the purpose this paper is to calculate the acoustic propagation loss across the strait where the range dependent characteristics are unique. Also the basic machanisms of the acoustic propagation based on the adiabtatic normal mode model will be discussed to show that the applicability of the coupled mode theory approach to this particular shallow environment. In section 2, a brife description of the environment is given to emphasize the unique characteristics of the locality. Also a possible separation of variables of the wave equation is discussed. In following section the adiabatic normal mode model and the methods of the numerical calculations is introduced based on the model called ADIAB that was developed by the Applied Research Laboratories, the University of Texas at Austin. Numerical results and the discussion will be followed.

II. RANGE-DEPENDENT ENVIRONMENT

In the wave equation the range dependent parameter is the wave number, $k=\frac{\omega}{C}$, where is the angular frequency and c is the sound speed that is function of vertical as well as

GEOACOUSTIC PROFILE

RANGE (KM) / LAYER	1 (0.1)			2 (9.4)			3 (15.2)			4 (27.5)			5 (37.4)			6 (52.6)		
	H	SPEED	ATEN	H	SPEED	ATEN	H	SPEED	ATEN	H	SPEED	ATEN	H	SPEED	ATEN	H	SPEED	ATEN
WATER	0	1513.0	0.0	0	1527.4	0.0	0	1527.4	0.0	0	1527.4	0.0	0	1522.8	0.0	0	1538.9	0.0
	30	1514.0	0.0	5	1522.8	0.0	15	1527.6	0.0	10	1523.0	0.0	20	1523.1	0.0	20	1539.2	0.0
				10	1516.1	0.0	25	1523.2	0.0	35	1523.4	0.0	45	1528.1	0.0	30	1546.3	0.0
				55	1516.1	0.0	40	1523.4	0.0	60	1523.8	0.0	90	1526.5	0.0	40	1541.8	0.0
							80	1524.1	0.0	95	1524.3	0.0	110	1524.6	0.0	50	1537.4	0.0
																60	1530.7	0.0
																90	1528.7	0.0
																110	1524.6	0.0
																180	1525.7	0.0
SEDIMENT	30	1520.0	0.1	55	1522.2	0.1	80	1572.7	0.15	95	1573.0	0.15	110	1707.4	0.5	180	1710.3	0.5
	50	1520.0	0.1	75	1522.2	0.1	95	1572.9	0.15	110	1573.0	0.15	120	1708.4	0.5	190	1710.3	0.5
SUBSTRATE	50	1820.0	0.5	75	1820.0	0.5	95		0.5	110	1820.0	0.5	120	1820.0	0.5	190	1820.0	0.5

H : DEPTH (m) , SPEED (m/s) , ATEN : ATTENUATION (dB/kHz)

* numbers in parenthesis are the ranges in km from start of track at which mode set is applied.

Table 1. Geoacoustic Profile

horizontal coordinates. The boundary conditions also give rise to the range dependence in terms of horizontal variation of the water depth and the sediment distributions. In the present model, the water depth changes from 30m to 180m over the horizontal distance of about 60Km range. The gradual deepening of the depth up to 37Km changes into a relatively steep slope at the range from 37Km to 52Km (Table 1).

The sound velocity profile also exhibits very unique horizontal changes. Over shallower region they are almost isovelocity media with slight negative gradient while in the deep region gradients change sign (even they are weak) along the depth. The unique distributions of the velocity profile are mainly due the effects of shallow water mixing and the advection of warm water in open sea area. For the sediment distribution along the path of sound propagation, almost uniform thickness of soft sediment layer exists above coarse sand as substrate. The soft sediment refers to clay in the shallow area and silt or silty-sand as the water becomes deeper.

III. ADIABATIC NORMAL MODE THEORY AND NUMERICAL IMPLEMTNATION

Adiabatic normal mode theory is an approximate form of the coupled mode theory: In a coupled mode theory of sound propagation the acoustic field due to a point source in a range variable medium is expressed as

$$\psi(z, r)=\sum_{n} R_n(r)\,\phi_n(z, r) \qquad (3.1)$$

In equation (3.1) ψ is the velocity potential and satisfies the following partial differential equation in cylindrical coordinates,

$$\nabla^2 \psi+k^2(z, r)\psi=-4\pi\delta(r-r_0) \qquad (3.2)$$

Where $k(x, r)$ is the wave number of the medium, which can vary with depth and range, and r_0 denotes the position of the point source. The particle velocity and acoustic pressure are to be continuous across all discontinuities in the medium. This requirements translates into the following boundary conditions on ψ. The continuity of particle velocity requires that the normal derivative of ψ, $\partial\psi/\partial n$ be continuous across surface of discontinuity. The continuity of pressure requires the $\psi\rho$ be continuous, where ρ is the material density of the medium. The boundary condition requiring continuity of normal derivative of ψ gives rise to an additional source of range dependence whenever sloping interfaces are present. In practice, the partial separation of range and depth variables implied in Eq.(3.1) requires that the normal derivative boundary conditions be approximated whenever sloping boundaries are present. This type of approximation does not affect the adiabatic approximation to coupled mode theory (12).

In Eq.(3. 1) the function are normal mode depth functions that satisfy at each point

$$\left[\frac{d^2}{dz^2}+k^2(z, r)-k_n^2(r)\right]\phi_n(z, r)=0 \qquad (3.3)$$

throughout the propagation path.

Across any interfaces in the path, $\rho\phi_n$ and $d\phi_n/dz$ are required to be continuous. In Eq. (3.3) the $k_n(r)$ are the normal mode eigenvalues which depend on range whenever the medium varies in range. The radial functions $R_n(r)$ in Eq.(3.1) satisfy the following set of coupled differential equations.

$$\left[\frac{d^2}{dz^2} + \frac{1}{r}\frac{d}{dr} + k_m^2(r) \right] R_m(r) = -\sum_n \left\{ A_{mn} R_n + B_{mn} \left(\frac{R_n}{r} + 2\frac{dR_n}{dr} \right) \right\} \tag{3.4}$$

The A_{mn} and B_{mn} are refered to as the coupling coefficients and are given by

$$A_{mn}(r) = \int_0^\infty \rho(z)\, \phi_m(z, r) \frac{\partial^2}{\partial r^2} \phi_n(z, r)\, dz \tag{3.5}$$

$$B_{mn}(r) = \int_0^\infty \rho(z)\, \phi_m(z, r) \frac{\partial \phi_n(z, r)}{\partial r}\, dz \tag{3.6}$$

In adiabatic approximation to coupled mode theory, the possibility of the coupling of energy between normal modes is ignored. This entails neglecting the coupling terms on the right-hand side of Eq.(3.4). The radial equation in the adibatic approximation therefore satisfies the following differential equation,

$$\left[\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} + k_m^2(r) \right] R_m(r) = 0 \tag{3.7}$$

The implementation of adiabatic normal mode theory to produce a numerical propagation loss model is accomplished in three basic steps. First, the medium is partitioned into range bins and a set of normal modes and eigenvalues for each bin is computed. This process is schematically illustrated in fig.1.

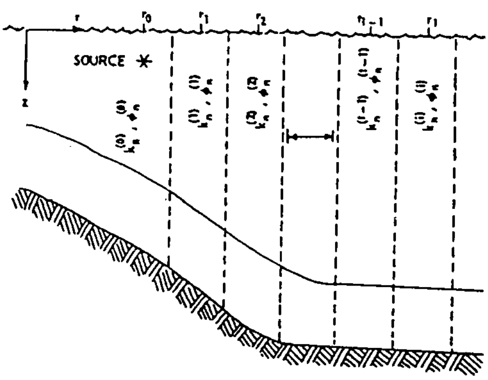

Fig. 1 Schematic diagram of partitioning of propagation path into range bins.

The mode calculations are carried out using NEMESIS(13), which numerically integrates Eq.(3.3) at the midpoint of the range bin, assuming locally horizontalinterfaces. The second stage of the calculations involves the calculation of mode attenuation coefficients for each range bin and fitting the eigenvalues through all the range bin midpoints using a cubic spline. The computation of the radial functions is done by using the WKB approximation and is given by

$$R_n(r) = \frac{A_n \exp\left(i \int^r k_n(x)\, dx\right)}{\sqrt{k_n(r)\, r}} \tag{3.8}$$

where A_n is a constant that depends on mode number. The final stage is to calculate the desired propagation loss between the field point and a point source. This numerical implementation of adiabatic normal mode theory can be accomplished by using the model ADIAB developed by the Applied Research Laboratories, the University of Texas at Austin(14).

IV. RESULTS OF CALCULATIONS

As shown in Fig.1, the source is located at r_0 where the depth of water is the shallowest. The source depth is chosen, at r_0 , as 10m, 20m and 30m while the receiver depth is 20m for 20m source and 10m or 30m for 30m source. The selection of source/receiver depths are based on the low frequency sound sources that are located close to the sea surface. Another reason for this selection is to see the bottom interaction in shallow water when the sound propagates bouncing back and forth at the interface.

The bathymetry for the propagation loss track is shown in Table 1. The gradual increase in depth of water changes into a relatively sharp increase within the last two bins. The thickness of sediment layer decreases slowly from the value of 20m in shallower bin to 10m in the deeper wate. However the attenuation values are increasing toward the deeper wster or along the downslope propagation path.

The subtrate is assumed to be coarse sand with sound velocity of 1820m/sec and has high attenuation value of 0.5 dB/m/KHz over the entire path.

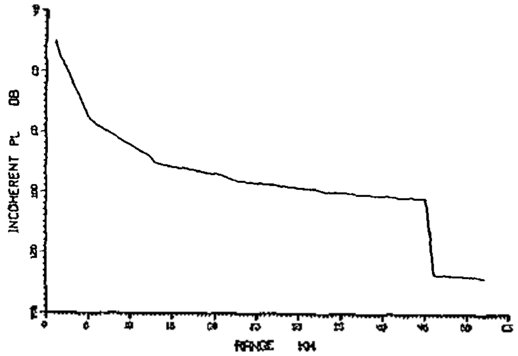

Fig. 2 Propagation loss versus range for source depth 10 m and receiver depth 30 m.

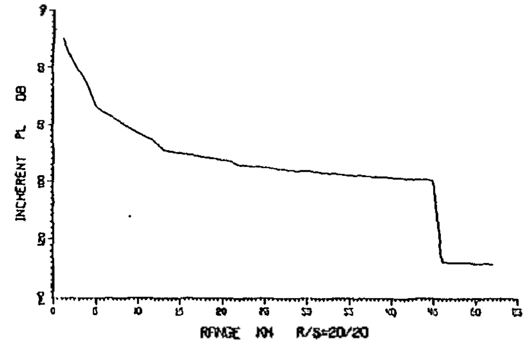

Fig. 3 Propagation loss versus range for source depth 20 m and receiver depth 20 m.

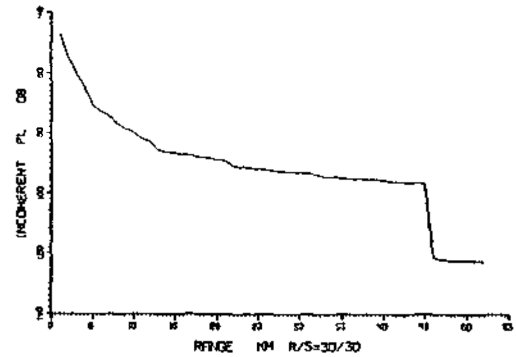

Fig. 4 Propagation loss versus range for source depth 30 m and receiver depth 30 m.

The figures 2,3 and 4 are the propagation loss calculations over the track. They are incoherent propagation loss obtained by summing the normal modes without regard to phase. The frequency of sound source used for the calculations is selected as 100Hz.

The basic mechanisms involved in acoustic propagation in a horizontally stratified medium are: spreading loss, attenuation loss due to bottom interaction effects, and intermode phasing effects. For a range variable bathymetry, an additional mechanism must be considered. This mechanism has been called the megaphone and inverse megaphone effect and is ralated to the changing acoustic energy density that accompanise bathymetry changes. In present case of downslope propagation this mechanism will act to produce additional loss and it has been called as *renormalization loss* (14). Therefore four defferent mechanisms are appeared to be involved in the results of calculations in the figures.

To illustrate these mechanisms independently from the each case consider Fig.2. Figure 2 shows the incoherent loss versus range for the 30mreceiver and the 10m source depths. The stairstepped curve in Fig.2 is resulted from the calculations such that a new range bin is entered and the mode functions change abruptly from those in the previous bin. In the shallow water regions only 4 discrete modes were possible. This number increased slowly bin by bin until, in the deep water, 13 mode were possible. In summing the normal modes to obrain the propagation loss the number of terms in the mode summations stays the same number corresponding to the shallow bin. Therefore whenever the mode number increases abrupthy a jump in the curve can be expected. To explain the loss in terms of the basic mechanism, first look at the spreading loss by taking the values at 20 and 40Km range. The spreading loss(SL) between the two ranges of 20 and 40Km is given by

$$SL = 10\log\left(\frac{40}{20}\right) \fallingdotseq 3.01\,\text{dB}$$

The renormalization loss(RL) can be estimated by assuming that the acoustic energy is effectively confined between the surface and substrate interfaces. With this assumption the RL is given by

$$RL \simeq 10\log\left(\frac{120}{95}\right) = 1\,\text{dB}$$

and the total loss between the two range is given by

$$RL + SL = 4\,\text{dB}$$

This result appears to be far less than the difference of about 7dB between two ranges. However, the attenuation effects and the mode sum effects should be considered to explain the difference. Since no attenuation is assumed in the water layer the sediment attenuation will be the dominant factor. The attenuation coefficient for the 40Km range is much greater than the 20Km range. Another important factor that must be considered to explain the difference in the propagation loss is the velocity profile at each range bin. For shallow source rays propagate downward and likely to have bottom interactions that causes loss due to sediment attenuation. From figures 3 and 4 it is shown that shallower source and receiver pair (Fig.3) produce less loss compared to the deeper source and receiver pair (Fig.4).

In the figures showing the propagation loss versus range a big jump in loss curve occurs at 45Km range and it amounts about 25dB. The geoacoustic profile (Table 1) shows that 45Km is the range from which the last deep water layer starts and also the bathymetry changes rapidly at that point. The reasons for the big jump could be explained in terms of mode summation as well as the changing character of the mode depth function. The mode number increases from 4 at the source to 13 in the last bin. However only 4 modes have been summed to produce the loss regardless of the number of modes possible in the last bin. This limits the applicability of the adiabatic approximation in a rapidly changing environment. In fact it was assumed at the beginning that a slowly changing medium is essential to apply the coupled mode theory to model the acoustic propagation in range-dependent media. In order to cause mode coupling to bè negligible and the adiabatic approximation to be valid Milder (7) discussed the conditions of applicability of the method such that frequency should be less than 600Hz and the range gradients of the velocity are less than or equal to 0.3m/sec over one nautical mile. But the loss is not solely due to the effects of the mode summation, it could be due to the mode depth function of the last bin.

To see how this contributes to the loss consider figures 5 and 6. Figure 5 depicts the normal mode depth function of mode 1 in the shallower region just before the last bin, and figure 6 depicts mode 1 in the last bin of the deep water region. In the shallow water region, mode 1 is a dominant mode because it interacts least with the bottom. Following mode 1 into the deep water, one would expect it to remain a dominant mode since it would have suffered less attenuation as it propagated through the shallow water. This, however, does not occur when the receiver is located at a shallow depth because mode 1 is evanescent at shallow depth. Therefore it does not contribute to the field in the deep water because of its changed character. It is not possible to isolate the individual effect on the propagation loss based on the present calculations to verify the big loss.

Figure 7 shows the grazing angle of the mode number possible in the last bin at the sediment interface. With high attenuation rate compared to the shallow region, the contribution of low modes to the field could be minimum. Therefore all the factors described above result in a big loss on the curve, at least, in tendency.

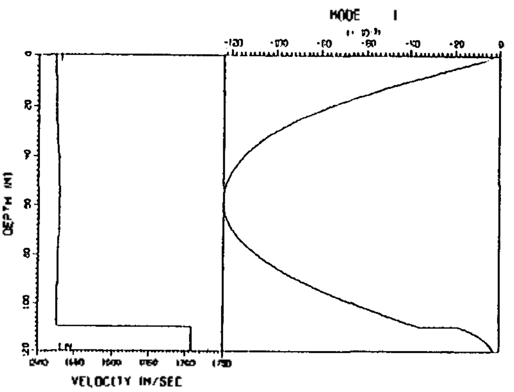

Fig. 5 Shallow water sound speed profile and mode function for mode number 1.

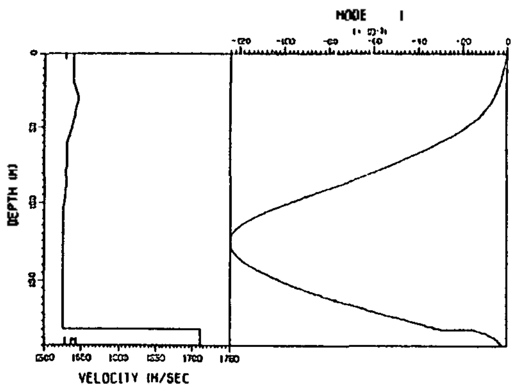

Fig. 6 Deep water sound speed profile and mode function for mode number 1.

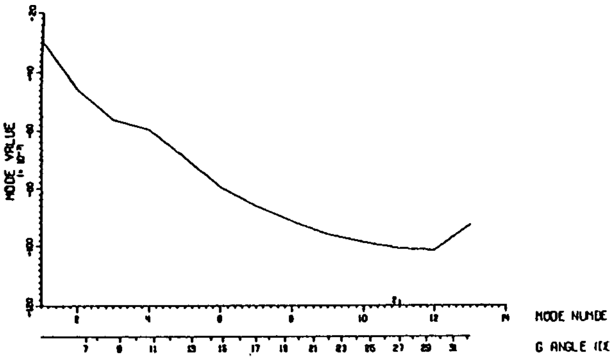

Fig. 7 Mode number and grazing angle at the sediment interface.

V. CONCLUSION

Adiabatic normal mode theory has been implemented to model the low frequency sound propagation in the range-dependent shallow water. For the present oceanic model it is very unique shallow water environment in that four different range varying parameters are involved, water sound velocity profile, sediment thickness attenuation coefficients, water depths. For shallow source and receiver depths the acoustic propagation involves spreading loss, attenuation loss due to bottom interaction effects, intermode phasing effects, renomralization loss. At the point of abrupt depth change a big jump in propagation loss occurs and the big loss can not be explained by the mechanisms involved in the propagation. It could be due to the changing character of the mode depth functions. Since mode function character is strongly dependent on the sound velocity profile, source-receiver depths should be also a significant factor contributing to the sound field.

It has been shown that in the shallow environment since higher modes are attenuated due to bottom interaction effects, lower modes depth functions and its characteristics are very important to predict sound propagation for the adiabatic normal mode calculation method. To show the mode function effects it would be necessary to locate the source at deep water region and move the receiver in the direction of upslope.

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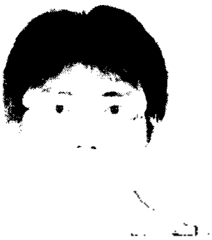

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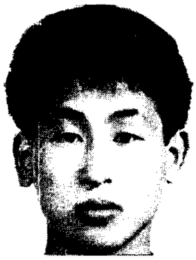

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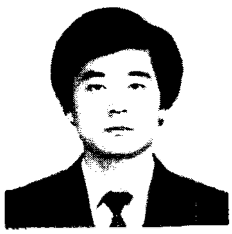

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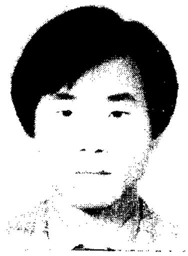

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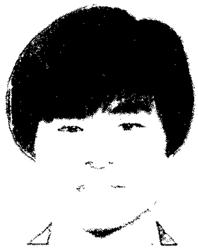

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