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Models for amplitude fluctuation of underwater acoustic narrow band signal based on modified modal scintillation index

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Abstract: A self-normalized statistic, the modified modal scintillation index (MMSI), is proposed and defined as the variance of the modulus of modal excitation normalized by the square of its expected value over some observation intervals. It is proved in an analytical form that the MMSI is a depth dependent signature and independent of the source level and the source range under the condition of the ideal waveguide, while the classical modal scintillation index (MSI) depends on both the source level and the source range. The MSI and the MMSI in the Pekeris waveguide at 70 Hz are simulated with different source levels and source ranges by the Kraken normal mode model. The simulation results are consistent with the theoretical deduction. The MMSI probability density functions (PDFs) of different normal modes for surface and submerged sources are calculated using the mode filtering methods with the same variations of vertical motions. It is indicated that the PDFs can be used to separate the submerged and the surface sources except for the fourth mode.

Key words: modified modal scintillation index; amplitude fluctuation; mode filtering; Pekeris waveguide

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The amplitude fluctuations of underwater narrow band signals have been studied for nearly 50 years. Researchers[1-4] summarized the most important causes of fluctuations in the power amplitudes of signals and noise propagating in the undersea acoustic environment. In recent years, it is still a focus in underwater signal processing. Katsnelson et al.[5-6] studied the frequency dependence and intensity fluctuations due to shallow water internal waves. Temporal variations of intensity fluctuations were found in experimental data. Comparisons of experimental results with theoretical estimates demonstrated good consistency. Colosi et al.[7-8] examined the second- and fourth-moment mode-amplitude statistics for low-frequency ocean sound propagation through random sound-speed perturbations in deep and shallow-water environments. Nair et al.[9] evaluated the fluctuation observed in the received signal with relevance to underwater systems. They defined the fluctuation index k as the standard deviation of the received signal with noise normalized by the standard deviation of noise. Stojanovic et al.[10] studied the random signal variations in underwater communication systems introduced by surface waves, internal turbulence, fluctuations in the sound speed, and other small-scale phenomena.

Among the above causes leading to sound fluctuations, the source and receiver depth instability may be the most obvious one. According to the normal mode theory, the amplitude of the normal modes are related to the source and receiver depths as well as the sea depth, sound speed profiles, surface and bottom conditions, and the signal frequency. The scintillation of modal energies has often been used to characterize and understand acoustic wave propagation in a randomly fluctuating ocean waveguide. Premus[11] introduced the modal scintillation index (MSI) for the purpose of surface and submerged source discrimination in a shallow water waveguide. The MSI is defined as the variance of the modulus of modal excitation normalized by its expected value over some observation intervals. The MSI of different normal modes exhibits different distributions when the received signal contains sea noise and it directly casts the source classification problem as a binary hypothesis test.

The MSI definition has its evident deficiency. It depends on the source level and the source range intensively. In this paper, a modified modal scintillation index (MMSI) is defined as the variance of the modulus of modal excitation normalized by the square of its expected value over some observation intervals. It is proved in an analytical form that the MMSI is only depth dependent. The modal excitations obtained from simulations are used to calculate the MMSI-depth curve of sources with different sound levels and ranges under a noise-free condition. Then the pseudo-inverse mode filter is used to estimate the probability density functions (PDFs) of the MMSI with Gaussian noise in the sinusoidal signal. The simulation results of the normal mode propagation model show

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that sources at different depths have different distribution parameters with the same depth fluctuation variations.

1 Theory of Modified Modal Scintillation Index

1.1 Definition of modal scintillation index

According to the normal mode theory, the complex pressure field can be expressed in terms of a superposition of normal modes in the far field of an acoustic source[12],

$$p(z, z_s, r_s) = A e^{-j\omega t} \sum_{m=1}^{M} \Phi_m(z_s) \Phi_m(z) \frac{\exp(j k_{rm} r_s)}{\sqrt{k_{rm} r_s}} \quad (1)$$

where z is the depth of the receiver; z_s is the depth of the acoustic source; $\Phi_m(z)$ represents the eigenfunction of the m-th mode; A is the amplitude of the source signal; M is the number of the normal modes; and r_s is the range between the source and the receiver. Suppose that the receiver is a vertical array with N hydrophones, and the depth of the i-th hydrophone is z_i, $i = 1, 2, \ldots, N$. The signal $\boldsymbol{p}$ received by the hydrophone array can be written in a matrix form as

$$\boldsymbol{p} = \boldsymbol{\Phi} \boldsymbol{H} \quad (2)$$

$$\boldsymbol{\Phi} = \begin{bmatrix} \Phi_1(z_1) & \Phi_2(z_1) & \ldots & \Phi_M(z_1) \\ \Phi_1(z_2) & \Phi_2(z_2) & \ldots & \Phi_M(z_2) \\ \vdots & \vdots & & \vdots \\ \Phi_1(z_N) & \Phi_2(z_N) & \ldots & \Phi_M(z_N) \end{bmatrix} \quad (3)$$

$$\boldsymbol{H} = \left[A e^{-j\omega t} \Phi_1(z_s) \frac{\exp(j k_{r1} r_s)}{\sqrt{k_{r1} r_s}} \quad \ldots \quad A e^{-j\omega t} \Phi_M(z_s) \frac{\exp(j k_{rM} r_s)}{\sqrt{k_{rM} r_s}} \right]^{T} = [\, h_1(z_s) \quad \ldots \quad h_m(z_s) \quad \ldots \quad h_M(z_s) \,] \quad (4)$$

where $\boldsymbol{\Phi}$ is the $N \times M$ matrix of normal mode functions; $\boldsymbol{H}$ is the $M \times 1$ vector of temporally varying modal excitations and depends on the depth of the acoustic source; and k_{rm} is the horizontal wavenumber. Premus[11] defined the modal scintillation index of the m-th mode as

$$S_{Im} = \frac{\mathrm{var}[\,|h_m(z_s)|\,]}{E[\,|h_m(z_s)|\,]} \quad (5)$$

For an acoustic source whose depth is fluctuating in response to wave interaction, the mode amplitude variance has a component which is a sensitive indicator of its mean depth. Mode amplitude fluctuations will exhibit high variance when the source is near the depth of a modal zero-crossing, where the derivative of the mode function is the maximum. Similarly, mode amplitudes fluctuate with a low variance for a source near a modal extremum, where the derivative of the mode function is zero. The critical property of the shallow waveguide which motivates the use of the modal scintillation index for binary depth classification is the fact that the normal modes are nearly sinusoidal and share a common zero-crossing at the surface[12] as shown in Fig. 1. Thus, a surface source with a given vertical motion variance will exhibit a high mode scintillation across all the modes. A submerged source with the same vertical motion variance will exhibit a low mode scintillation for at least one mode, due to its expected proximity to at least one modal extremum.

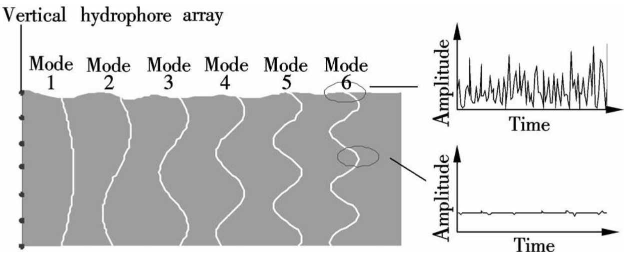

Fig. 1 Conceptual description of physics-based depth discrimination using MSI

Although the physical mechanism of utilizing the MSI to discriminate surface source and submerged source is reasonable, the definition in Eq. (5) is not a self-normalized statistic. The value of the MSI depends remarkably on the source level and source range. And this will be analytically proved in the following section.

1.2 Performance analysis of modal scintillation index

Consider the isovelocity waveguide as shown in Fig. 2. The sound speed is a constant value c at all depths. D is the waveguide depth and ρ is the density of water.

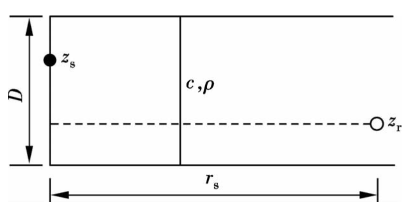

Fig. 2 Schematic of the isovelocity waveguide

The horizontal wavenumber can be calculated as [12]

$$k_{rm} = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left[\left(m - \frac{1}{2}\right)\frac{\pi}{D}\right]^2} \qquad m = 1, 2, \ldots \quad (6)$$

and the corresponding eigenfunctions are given by

$$\Phi_m(z) = \sqrt{\frac{2\rho}{D}} \sin(k_{zm} z) \quad (7)$$

where k_{zm} is the vertical wavenumber and it is given by

$$k_{zm} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_{rm}^2} = \left(m - \frac{1}{2}\right)\frac{\pi}{D} \qquad m = 1, 2, \ldots \quad (8)$$

Suppose that the vertical motion of acoustic source Δz is random and that it follows the Gaussian distribution $N(0, \sigma^2)$, and the mean acoustic source depth is z_{s0}. The eigenfunctions in Eq. (7) can be modified as

$$\Phi_m(z_s) = C\sin[k_{zm}(z_{s0} + \Delta z)] = C\sin(k_{zm} z_{s0})\cos(k_{zm}\Delta z) + C\cos(k_{zm} z_{s0})\sin(k_{zm}\Delta z) \quad (9)$$

where $C=(2\rho/D)^{1/2}$. Since the approximation condition

$$k_{zm}=\sqrt{\left(\frac{\omega}{c}\right)^2-k_{rm}^2}\ll 1 \tag{10}$$

is satisfied in most low frequency narrow band signals in the far field situations (low order normal modes are dominant), Eq. (9) can be simplified as

$$\Phi_m(z_s)\approx C[\sin(k_{zm}z_{s0})+\cos(k_{zm}z_{s0})k_{zm}\Delta z] \tag{11}$$

Evidently, the eigenfunctions $\Phi_m(z_s)$ follows the Gaussian distribution $N(\mu_\Phi,\sigma_\Phi^2)$, where

$$\mu_\Phi=C\sin(k_{zm}z_{s0}),\quad \sigma_\Phi^2=C^2\cos^2(k_{zm}z_{s0})k_{zm}^2 \tag{12}$$

With Eq. (4), $|h_m(z_s)|$ can be written as

$$|h_m(z_s)|=\left|A\Phi_m(z_s)\frac{\exp(\mathrm{j}k_{rm}r_s)}{\sqrt{k_{rm}r_s}}\right|=\left|\frac{A\Phi_m(z_s)}{\sqrt{k_{rm}r_s}}\right|=\left|\frac{A}{\sqrt{k_{rm}r_s}}\Phi_m(z_s)\right|=|K\Phi_m(z_s)| \tag{13}$$

where $K=A/(k_{rm}r_s)^{1/2}$. Using the properties of the Gaussian random variable, $h_m(z_s)$ follows the Gaussian distribution $N(\mu_{K\Phi},\sigma_{K\Phi}^2)$, where

$$\mu_{K\Phi}=KC\sin(k_{zm}z_{s0}),\quad \sigma_{K\Phi}^2=K^2C^2\cos^2(k_{zm}z_{s0})k_{zm}^2 \tag{14}$$

And $|h_m(z_s)|$ follows the folded Gaussian distribution[13]. Its mathematical expectation and variance are given by

$$E[|h_m|]=\frac{1}{\sqrt{2\pi}}\int_{-\mu_{K\Phi}/\sigma_{K\Phi}}^{\mu_{K\Phi}/\sigma_{K\Phi}}\mathrm{e}^{-t^2/2}\mathrm{d}t+\sigma\sqrt{\frac{2}{\pi}}\mathrm{e}^{-\mu_{K\Phi}^2/(2\sigma_{K\Phi}^2)}=\mathrm{erf}\left(\frac{\mu_{K\Phi}}{2\sigma_{K\Phi}}\right)+\sigma\sqrt{\frac{2}{\pi}}\mathrm{e}^{-\mu_{K\Phi}^2/(2\sigma_{K\Phi}^2)} \tag{15}$$

$$\mathrm{var}[|h_m|]=\sigma_{K\Phi}^2+\mu_{K\Phi}^2-E^2[|h_m|] \tag{16}$$

Substituting Eqs. (12), (15) and (16) into Eq. (5), the modal scintillation index can be expressed as

$$S_{\mathrm{I}m}=\frac{\mathrm{var}[|h_m|]}{E[|h_m|]}=\frac{\sigma_{K\Phi}^2+\mu_{K\Phi}^2-E^2[|h_m|]}{E[|h_m|]}=\frac{(KC)^2\cos^2(k_{zm}z_{s0})k_{zm}^2+(KC)^2\sin^2(k_{zm}z_{s0})}{\mathrm{erf}\left(\frac{\mu_{K\Phi}}{2\sigma_{K\Phi}}\right)+KC\sqrt{\frac{2}{\pi}}\mathrm{e}^{-\mu_{K\Phi}^2/(2\sigma_{K\Phi}^2)}}-\mathrm{erf}\left(\frac{\mu_{K\Phi}}{2\sigma_{K\Phi}}\right)-KC\sqrt{\frac{2}{\pi}}\mathrm{e}^{-\mu_{K\Phi}^2/(2\sigma_{K\Phi}^2)} \tag{17}$$

where erf(·) is the error function and has the maximum value of 1. When $KC\gg 1$, further simplification can be made as

$$S_{\mathrm{I}m}\approx KC\left[\frac{\cos^2(k_{zm}z_{s0})k_{zm}^2+\sin^2(k_{zm}z_{s0})}{\sqrt{2/\pi}\,\mathrm{e}^{-\mu_{K\Phi}^2/(2\sigma_{K\Phi}^2)}}\right]-\mathrm{erf}\left(\frac{\mu_{K\Phi}}{2\sigma_{K\Phi}}\right)-KC\cos(k_{zm}z_{s0})k_{zm} \tag{18}$$

Since K is the function of source level A and source range r_s, $S_{\mathrm{I}m}$ is a source level and source range dependent statistic.

1.3 Definition of modified modal scintillation index

In section 1.2, it is analytically proved that the values of the MSI depend not only on the source depth, but also on the source level and source range. It means that a near submerged source may also exhibit high mode scintillation, and the binary discrimination method using the MSI is only valid when the surface source and submerged source have the same K value. Since this condition cannot always be satisfied, another statistic independent of K must be defined to work robustly. Define the MMSI as

$$S'_{\mathrm{I}m}=\frac{\mathrm{var}[|h_m|]}{E^2[|h_m|]} \tag{19}$$

Using a similar simplifying method, $S'_{\mathrm{I}m}$ are given in an approximative form as

$$S'_{\mathrm{I}m}=\frac{\mathrm{var}[|h_m|]}{E^2[|h_m|]}=\frac{\sigma_{K\Phi}^2+\mu_{K\Phi}^2-E^2[|h_m|]}{E^2[|h_m|]}\approx\frac{\cos^2(k_{zm}z_{s0})k_{zm}^2+\sin^2(k_{zm}z_{s0})}{2/\pi\,\mathrm{e}^{-2\mu_{K\Phi}^2/(2\sigma_{K\Phi}^2)}} \tag{20}$$

Eq. (20) shows that $S'_{\mathrm{I}m}$ is a source depth dependent statistic only and independent of the source level and the source range.

In practice, the MMSI must be estimated from the received signal with noise. The model with additive noise in signals received by the array is

$$\boldsymbol{p}=\boldsymbol{\Phi}\boldsymbol{H}+\boldsymbol{n} \tag{21}$$

where $\boldsymbol{n}$ is the additive ambient noise vector $\{n_1, n_2, \ldots n_N\}^{\mathrm{T}}$ and $n_i(i=1,2,\ldots N)$ is the noise at the i-th hydrophone. The modal excitation vector can be computed from samples of the received pressure field via the pseudo-inverse calculation given by

$$\hat{\boldsymbol{H}}=\boldsymbol{\Phi}^+\boldsymbol{p}=\boldsymbol{H}+\boldsymbol{\Phi}^+\boldsymbol{n} \tag{22}$$

where $\boldsymbol{\Phi}^+=(\boldsymbol{\Phi}^{\mathrm{H}}\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^{\mathrm{H}}$ represents the pseudo-inverse of $\boldsymbol{\Phi}$ and the superscript H denotes conjugate transpose. Suppose that the additive noise $\boldsymbol{n}$ is the zero mean Gaussian random process, and $\hat{\boldsymbol{H}}$ is the unbiased estimation of $\boldsymbol{H}$. Substituting Eq. (22) into Eq. (19), the MMSI can be estimated from the received signal.

2 Simulation results and discussion

To illustrate the utility of the modified modal scintillation index, a simulation experiment is performed for the Pekeris waveguide[12]. The simulation geometry is depicted in Fig. 3. The waveguide depth D is 100 m; the sound speed in the water c is 1 500 m/s; the density of the water ρ is 1 000 kg/m^3; the sound speed in the bottom c_b is 2 000 m/s; and the density of the bottom ρ_b is 1 000 kg/m^3. The source is a narrow band source and its frequency is 70 Hz. The receiver is a fully spanning vertical array consisting of 41 hydrophones equally spaced at 2.5 m. There are six modes that can propagate in the Pekeris waveguide at the frequency of 70 Hz. The mode shapes are depicted in Fig. 4. The vertical motion of source follows the Gaussian distribution $N(0,1)$.

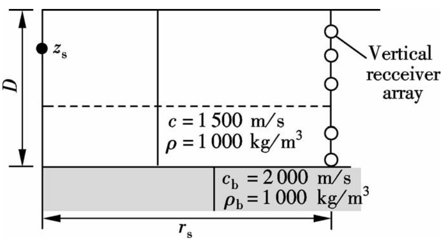

Fig. 3 Schematic of the Pekeris waveguide

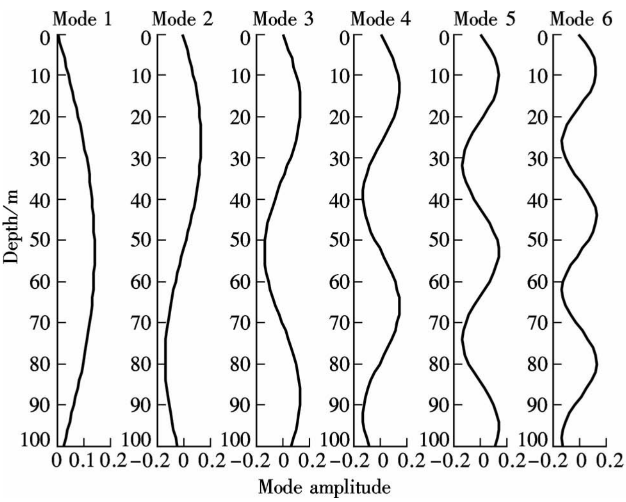

Fig. 4 Normal modes in Pekeris waveguide

The simulation experiment consists of three parts. First, the MSI and the MMSI are calculated by using the analytical form for sources of different sound levels with the source depth varying from 5 to 90 m. Secondly, the MSI and the MMSI are calculated by using the analytical form for sources of different ranges with the source depth varying from 5 to 90 m. The first two parts are under the condition free of noise. In the third part, the MMSI distribution is simulated with noise in the received signal for surface and submerged sources.

2.1 MSI and MMSI of sources with different sound levels

The Kraken normal mode model[14] is used to calculate the eigenfunctions Φ_m, the horizontal wavenumber k_{rm} and the vertical wavenumber k_{zm}. Then Φ_m, k_{rm} and k_{zm} are inserted into Eq. (4), Eq. (5) and Eq. (19) to calculate the modal excitations $\boldsymbol{H}$ analytically for acoustic source with the source levels of 160 and 130 dB. The source level is in units of dB re: 1 μPa · m. The source range is 5 km. The MSI-depth and MMSI-depth curves are depicted in Fig. 5.

The results in Fig. 5 show that both the MSI and the MMSI exhibit high mode amplitude fluctuation variances at the depth of modal zero-crossing. In Figs. 5(a), (c) and (e), there is a great disparity between the two curves of sources with different source levels. In Figs. 5(b), (d) and (f), the two curves of sources with different source levels match well. This means that the MSI is a source level sensitive statistic while the MMSI is not.

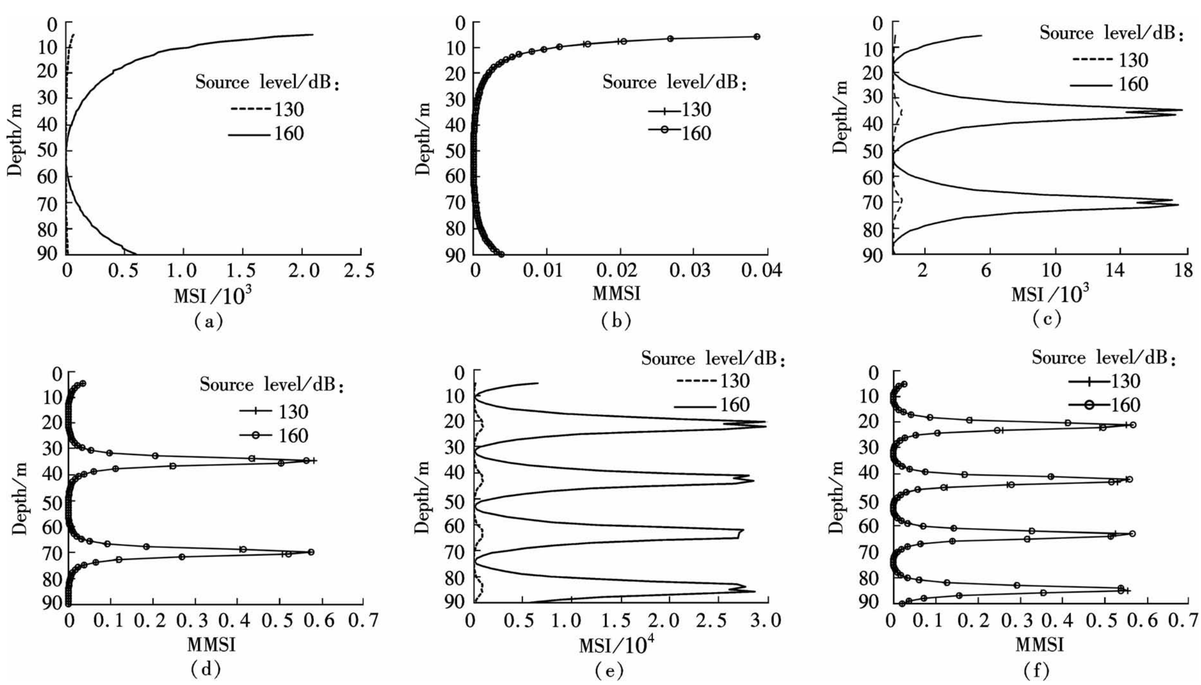

Fig. 5 MSI-depth and MMSI-depth curves for different source levels. (a) MSI-depth curve of Mode 1; (b) MMSI-depth curve of Mode 1; (c) MSI-depth curve of Mode 3; (d) MMSI-depth curve of Mode 3; (e) MSI-depth curve of Mode 5; (f) MMSI-depth curve of Mode 5

2.2 MSI and MMSI of sources with different ranges

The same algorithm as in Section 2.1 is used to calculate the modal excitations $\boldsymbol{H}$ for acoustic source with the source ranges of 5 and 10 km. The source level is 160 dB. The results are depicted in Fig. 6.

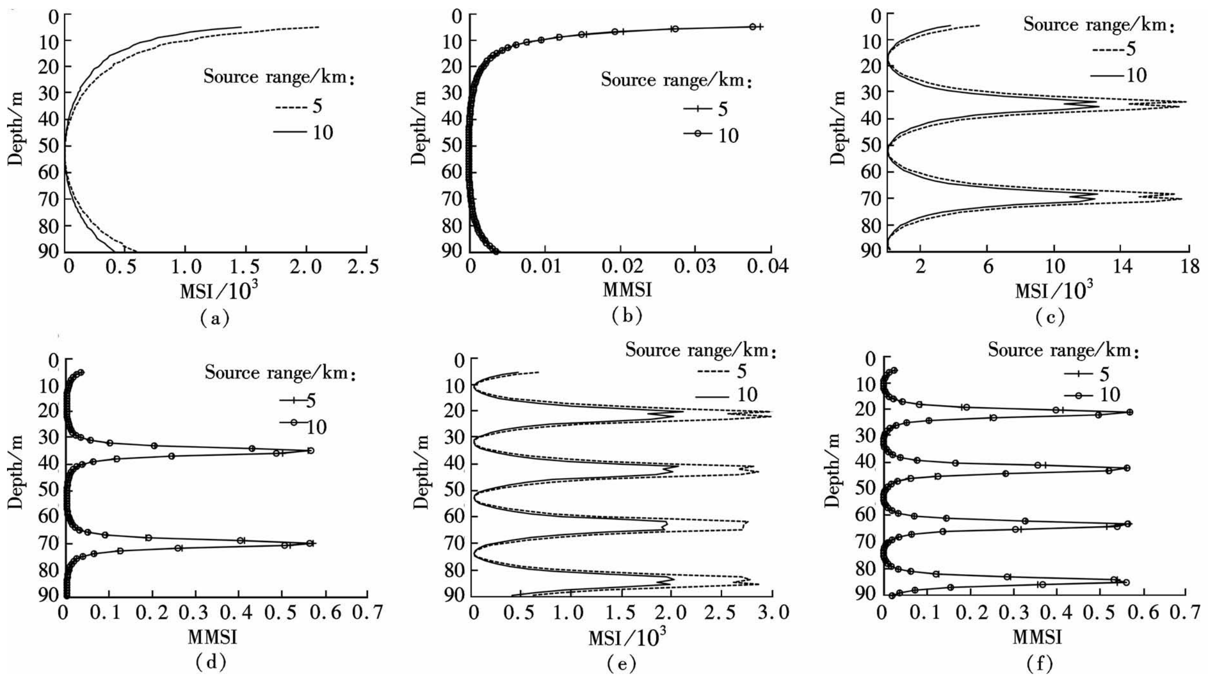

Fig. 6 MSI-depth and MMSI-depth curves for different source ranges. (a) MSI-depth curve of Mode 1; (b) MMSI-depth curve of Mode 1; (c) MSI-depth curve of Mode 3; (d) MMSI-depth curve of Mode 3; (e) MSI-depth curve of Mode 5; (f) MMSI-depth curve of Mode 5

The results in Fig. 6 show that both the MSI and the MMSI exhibit high mode amplitude fluctuation variances at the depth of modal zero-crossing. In Figs. 6(a), (c) and (e), there is a small disparity between the two curves of sources with different source levels. In Figs. 6(b), (d) and (f), the two curves of sources with different source levels match well. This means that the range variation does not affect the MSI as greatly as the source level variation does. The MMSI is a self-normalized statistic and independent of source range.

2.3 MMSI probability density functions estimation

In Section 2.1 and Section 2.2, both the MSI and the MMSI are analytically calculated without noise. But in real applications, the ambient noise cannot be ignored. The hydrophone array receives the signal from the acoustic source as well as the ambient noise. The noise field in this simulation experiment is modeled as the spatial white Gaussian noise with a noise spectrum level of 65 dB re: 1 μPa · m. The Kraken normal mode model is also used to calculate Φ_m, k_{rm} and k_{zm}. Considering the effect of the ambient noise, only the estimation of the modal excitations $\boldsymbol{H}$ can be obtained from Eq. (22) by using the pseudo-inverse mode filter. In this case, the statistic MMSI is modeled as a distribution depending on the vertical motion and ambient noise.

A submerged source and a surface source are considered in the simulation experiment. Fig. 7 shows the estimated PDFs of six modified modal scintillation indices obtained from Monte Carlo simulations using 1 000 trials under each hypothesis. The submerged source PDF is denoted as $p(\mathrm{MMSI} \mid H_{\mathrm{sub}})$ and the surface source PDF is denoted as $p(\mathrm{MMSI} \mid H_{\mathrm{surf}})$. The source range is 5 km and the source level is 160 dB in each case.

Fig. 7 shows that the PDFs of the modified modal scintillation indices of the submerged source separates to the left of that of the surface source in the direction of small values of the MMSI in most cases except for mode 4. The positions of the PDFs of surface sources are relatively fixed on the axis of log(MMSI), while the positions of the PDFs of submerged sources shifted along the axis of log(MMSI). This phenomenon shows that the surface source is near the depth of modal zero-crossing for all the modes and exhibits a high variance of mode amplitudes. The submerged source is near the depth of mode zero-crossing for some modes (mode 3 and mode 4) and near the depth of mode extremums for other modes (mode 1, mode 2, mode 5 and mode 6). This attribute can be used to discriminate the submerged and surface sources.

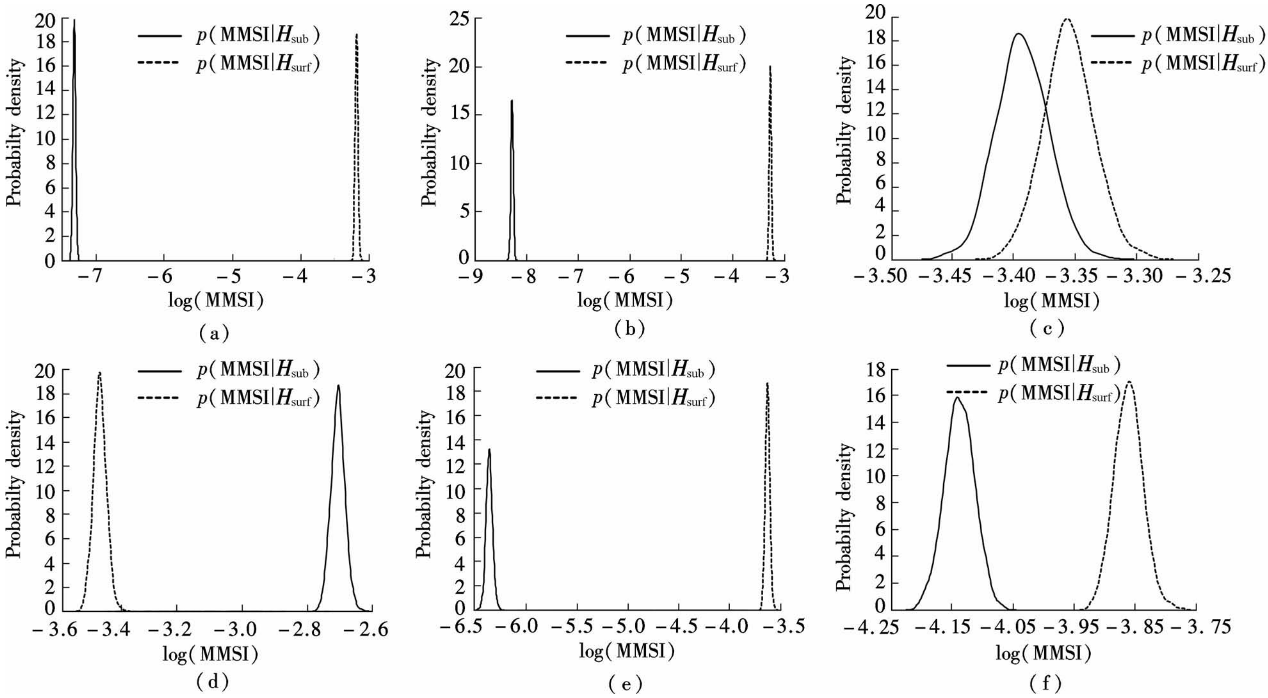

Fig. 7 Estimated PDF for MMSI. (a) Mode 1; (b) Mode 2; (c) Mode 3; (d) Mode 4; (e) Mode 5; (f) Mode 6

3 Conclusion

A modified modal scintillation index is proposed in this paper. It is analytically proved that the MMSI is a depth dependent signature and independent of the source level and range under the condition of the ideal waveguide, while the MSI is both source level and range dependent. A simulation experiment which consists of three parts is performed for the Pekeris waveguide to illustrate the utility of the modified modal scintillation index. The simulation results show that the MMSI is a self-normalized statistic while the MSI is not. The MMSI probability density functions of submerged and surface sources separate from each other in most modes with the same vertical motion variance. And this attribute can be regarded as the signature to discriminate underwater acoustic sources.

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基于修正模式闪烁指数的水声窄带信号幅度波动模型

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摘要：提出了一种自归一化的修正模式闪烁指数，定义为一段观测时间内模式激励函数模的方差与模式激励函数模的数学期望平方的比值. 在理想水声波导的条件下，解析地证明了修正模式闪烁指数是一种与目标深度相关、与目标距离和强度无关的统计量，而传统的模式闪烁指数与目标距离和强度都相关. 利用 Kraken 简正波模型进行了 Pekeris 波导中的不同目标强度和距离情况下的模式闪烁指数和修正模式闪烁指数计算仿真，信号频率为 70 Hz. 仿真结果与理论推导的结果一致. 在相同的目标垂直运动方差情况下，利用简正波过滤的方法进行了水下目标和水面目标的修正模式闪烁指数概率密度函数的估计. 计算结果表明，除了 4 号简正波模式外，其余简正波模式的修正模式闪烁指数概率密度函数可以用来区分水下和水面目标.

关键词：修正模式闪烁指数；幅度波动；简正波模式过滤；Pekeris 波导

中图分类号：O427.3