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SIMPLE TECHNIQUE FOR MODELLING AND RECOMPRESSING SH TYPE CHANNEL WAVES

T. BODOKY*, E. CZILLER*, A. KÖRMENDI**

The increasing importance of in-seam seismic techniques used in coal mines necessitates a better understanding of seismic channel waves. To achieve this goal different numerical modelling techniques have been developed for studying the different types of these waves under arbitrary conditions.

A simple numerical model of SH type channel waves is presented and utilized to derive a recompressing filter to remove dispersion of the waves.

Simple model of SH type waves in a seismic wave guiding channel

When studying the propagation of SH type waves in a seam we can use a similar scheme of the raypaths to that used by Burg et al. to explain seismic repetitive patterns in shallow water *(Fig. 1)*. We consider the wave propagation in a seam having parallel plain boundaries and a thickness H. The distance between the source and the receiver is x. For simplicity's sake we assume symmetry in the model, i.e. both the source and the receiver are placed in the middle of the seam and the distortional waves have the same velocity both in the upper- and underlying layers. If this velocity is V_2 and that in the seam V_1, then $V_2 > V_1$.

There are a great number of possible raypaths between the source and the receiver because of the reflections on boundaries of the seam. Thus, at the receiver, the wavelets, which have propagated along different raypaths and have different arrival times, are subjected to interference and this interference is recorded as a seamwave wavelet. In the formation of this interference, two factors play important roles:

a) a series of "geometrical delays" coming from the geometrical length of raypaths,

b) phase shifts occurring at total reflections. The lengths of the raypaths and the travel times belonging to them are given by the geometry of the model. If the travel times are represented by τ, then in the case of n reflections

$$\tau_n = \frac{1}{V_1}\sqrt{(nH)^2 + x^2}. \tag{1}$$

The phase shifts are independent of frequency at the total reflection of SH type waves and are given by the formula

* Eötvös Loránd Geophysical Institute (ELGI) of Hungary.
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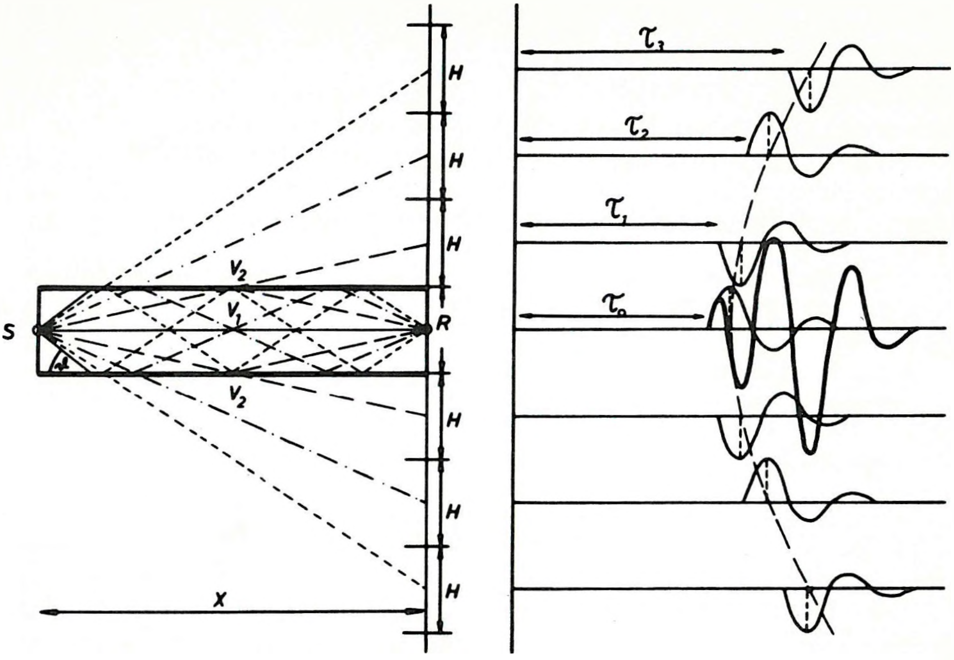

Fig. 1. A scheme of the raypaths and the "geometrical delays" in a wave guiding channel

1. ábra. A geometriai késleltetések vázlata egy hullámvezetőben

Фиг. 1. Схема геометрических задержек в волноводе

$$\psi(\vartheta) = -2\arctan\left(\frac{\varrho_2 V_2}{\varrho_1 V_1}\,\frac{\sqrt{\frac{V_2^2}{V_1^2}\cos^2\vartheta - 1}}{\sin\vartheta}\right), \tag{2}$$

where ψ is the phase shift, ϑ the angle made by the raypath with the boundary of the seam, and ϱ is the density.

If a raypath involves n total reflections then its total phase shift is

$$\psi_n = n\psi(\vartheta_n), \tag{3}$$

where ϑ_n comes also from the geometry of the model:

$$\vartheta_n = \arctan\frac{nH}{x}. \tag{4}$$

Now, if we denote the source signal as $S(t)$, the Fourier series of $S(t)$ can be written as

$$S(t) = \frac{A_0}{2} + \sum_k A_k \cos(\omega kt + \varphi_k), \tag{5}$$

where the series A_k is the amplitude spectrum and the series φ_k is the phase spectrum of $S(t)$.

From the source signal the dispersed in-seam wavelet can be derived by summing all source signals propagating along the possible raypaths and undergoing the attendant phase shifts. If the dispersed wavelet is denoted as $W(t)$ then

$$W(t) = S(t) + 2 \sum_{n=1}^{m} \sum_k A_k \cos[\omega k(t-\tau_n) + \varphi_k + \psi_n]. \tag{6}$$

The number of summands (m) can be determined from the critical angle. The summation has to be continued to the last direction having a ϑ_n smaller than the critical angle, viz.

$$\vartheta_m \leqq \arccos \frac{V_1}{V_2} \leqq \vartheta_{m+1}.$$

The model can be made better by weighting the summands proportionally to their source angles and inversely proportionally to the length of their raypaths. So the last form of the model is

$$W(t) = \sum_{n=0}^{m} \frac{b_n}{\tau_n} \sum_k A_k \cos[\omega k(t-\tau_n) + \varphi_k + \psi_n], \tag{7}$$

where b_n is given by the formulae

$$b_0 = 1$$

$$b_n = \frac{\beta_n - \beta_{n-1}}{\beta_0} \quad \text{if} \quad n = 1, 2, \ldots, m.$$

$$\beta_n = \arctan \frac{(2n+1)H}{2x}.$$

Formula (7) describes what we call the numerical model of the dispersed SH type channel wave wavelet. In the following we try to decompose the interference wavelet on the basis of this formula.

Simple recompression filter derived from the described model

The effect of the series of geometrical delays may be described as a convolution with a $G(x)$ function, where $G(x)$ takes the form

$$G(x) = \sum_{n=0}^{m} \frac{b_n}{\tau_n} \delta(\tau_n), \tag{8}$$

where δ denotes the Dirac function.

The $G(x)$ function has a special feature: its autocorrelation function is characterized by a sharp impulse-like main peak with comparatively very small side lobes. This behaviour can be used to eliminate the effect of geometrical delays, namely if $W(t)$ is correlated by $G(x)$ then the "short" autocorrelation function of $G(x)$ will step into the place of the "long" $G(x)$ function in the original convolution. Thus the dispersed wavelet will be significantly shorter, it will be decompressed.

In real practice however, the source-receiver (source image-receiver) distance, x, is not known therefore we have substituted the t variable for the fixed x value using the $x = tV_1$ equation. Neglecting the coefficients of delta functions, in this way the following filter operator is obtained:

$$g(t) = \sum_{n=0}^{m} \delta(\tau_n). \tag{9}$$

To see the effect of this filter a model using phase inversion instead of phase shifts was computed and filtered.

Figure 2 shows the source signal, the dispersed wavelet and the filtered result. As can be seen, the dispersed wavelet is not only recompressed by the filter in an effective manner but also placed exactly where it could have been expected if it had propagated as a regular S type bodywave.

The elimination of the phase shift of a single frequency can be done in a similar way. The phase shifts have to be converted into time delays and these have to be built into the filter operator.

$$U_{nk} = \frac{\psi_n}{2\pi} T_k,$$

where T_k is the period of the given f_k single frequency:

$$g(t, f_k) = \sum_{n=0}^{m} \delta(\tau_n + U_{nk}). \tag{10}$$

For accuracy, the measured trace must be reduced to its frequency components and the filtering must be performed on each component with the appropriate operator. After filtering, the components have to be summed again.

The solution described above is correct, but it is by no means simple. For this reason we decided to use the following approach:

the measured trace is filtered by several band-pass filters. The band-pass filters are zero-phase filters possessing triangle-shaped transfer functions. The

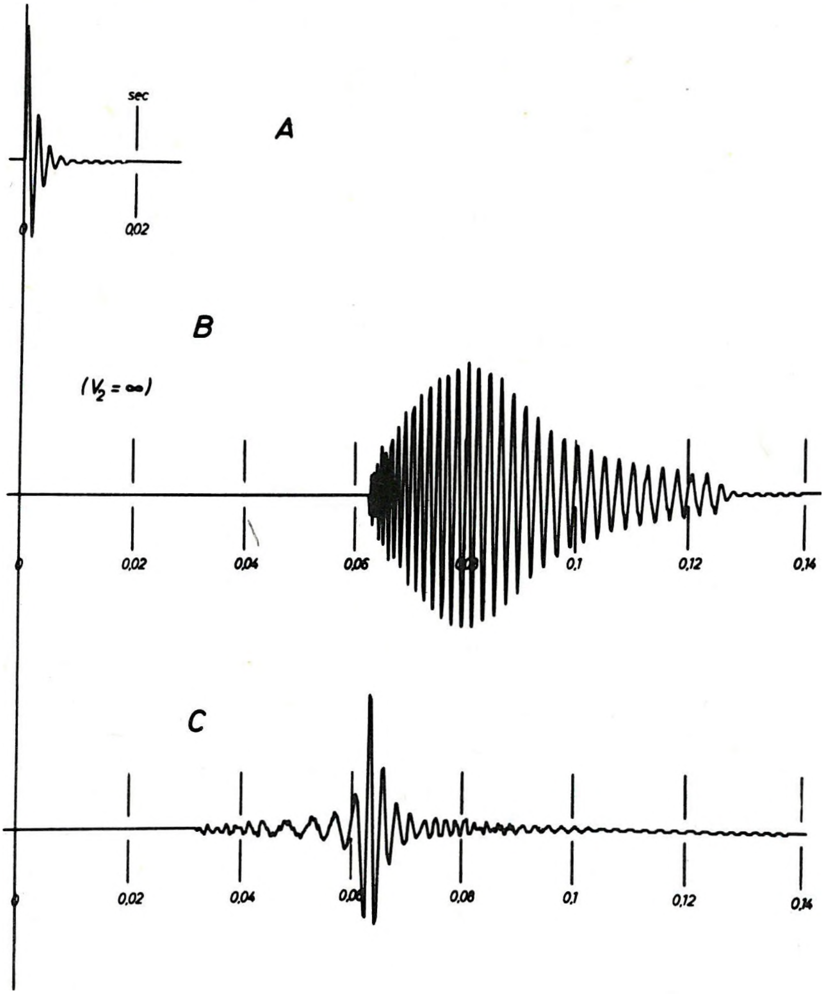

Fig. 2. A — source signal; B — dispersed wavelet; C — filtered wavelet

2. ábra. A — indulójel; B — diszperz csatornahullám; C — szűrt csatornahullám

Фиг. 2. А — Исходный сигнал; В — Дисперсная канальная волна; С — Отфильтрованная канальная волна

lower and upper frequency limits of the transfer functions fall to the peak frequency of the neighbouring ones *(Fig. 3)*. The band-pass filtered versions are correlated by the above described $g(t, f_k)$ operator, in which f_k is the peak frequency of the applied band-pass filter. After the correlation the different versions are summed and the result can then be band-pass filtered again.

This simplified way means that the original task is solved exactly only at the peak frequencies of the band-pass filters. All other frequency components of the filtered trace are obtained as a sum from the two neighbouring filtered versions.

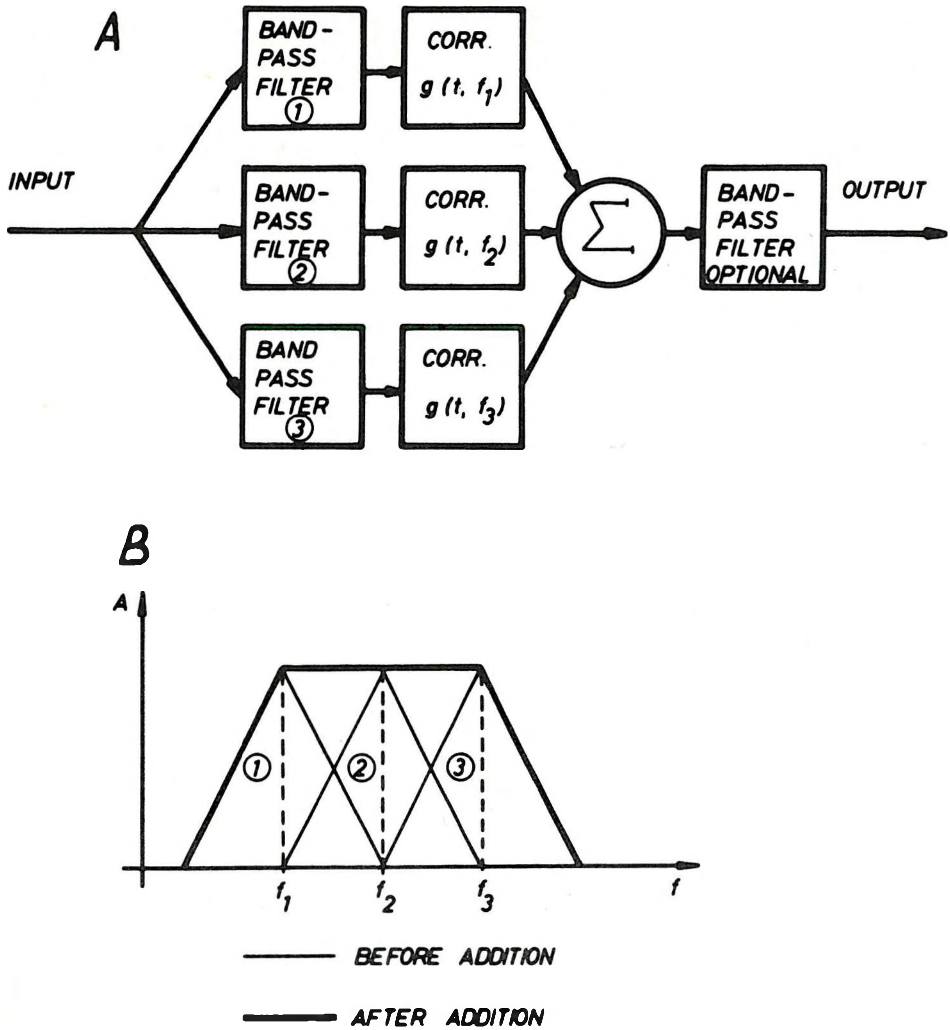

Fig. 3. The scheme of the proposed filtering
A — block diagram; B — transfer functions

3. ábra. A javasolt szűrési eljárás vázlata
A — blokkdiagram; B — átviteli függvények

Фиг. 3. Схема предложенного способа фильтрации А — Блок-схема; В — Частотные характеристики

To illustrate the effectiveness of the procedure three dispersed wavelet models and their filtered versions are shown. For the model computations the source signals were different but the other parameters were the same: ($x = 100$ m, $H = 2.5$ m, $V_1 = 1{,}600$ m/s, $V_1/V_2 = 0.5$ and $\varrho_1/\varrho_2 = 0.5$).

In *Fig. 4* the spectrum of the source signal expands from 100 to 400 Hz. The dispersed wavelet model is significantly delayed compared with the expected arrival time of an S type bodywave propagating with velocity V_1, but it is not attenuated very much. For its filtering, five band-pass filters were used. As a result of the applied procedure the main peak of the filtered wavelet indicates precisely the arrival time belonging to V_1, and the wavelet has become shorter. If the processed wavelet is compared with the source signal it can be seen that the former is no more than 50% longer than the latter.

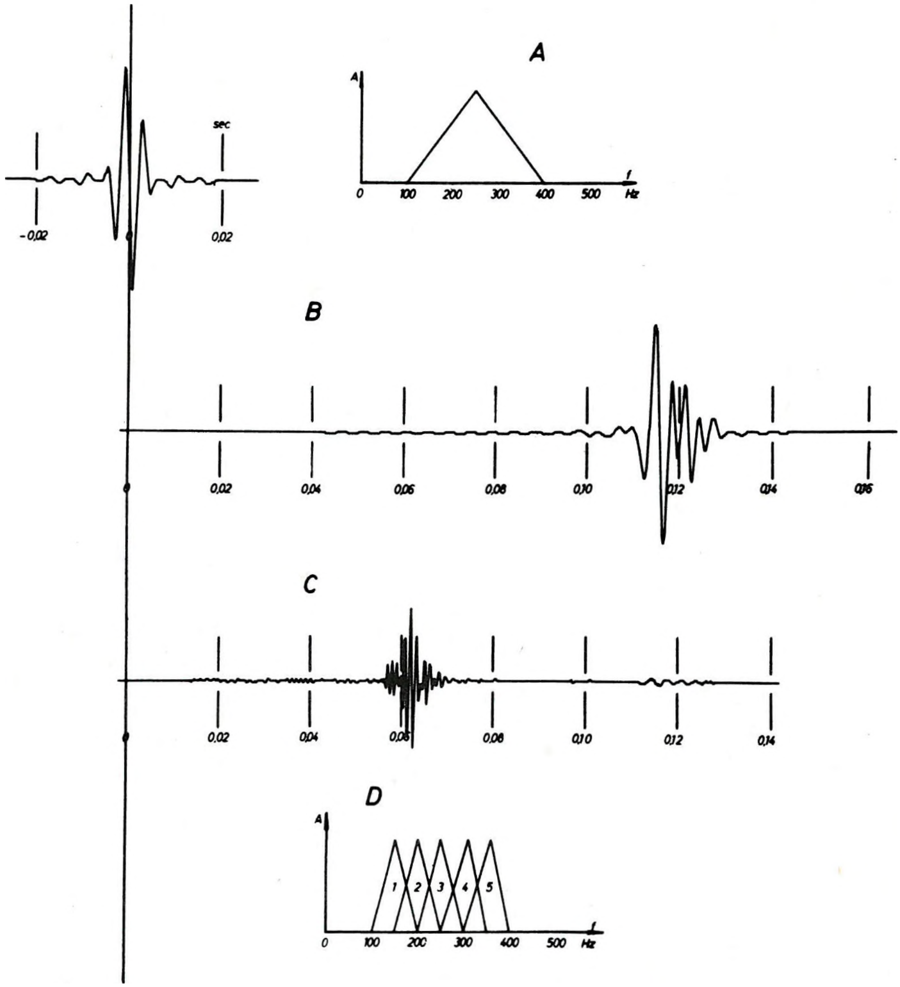

Fig. 4. A — source signal and its spectrum; B — dispersed wavelet; C — filtered wavelet; D — transfer functions of the used bandpass filters

4. ábra. A — az indulójel és spektruma; B — diszperz csatornahullám; C — szűrt csatornahullám; D — a használt sávszűrők átviteli függvényei

Фиг. 4. A – Исходный сигнал и его спектр; B – Дисперсная канальная волна; C – Отфильтрованная канальная волна; D – Частотные характеристики использованных полосовых фильтров

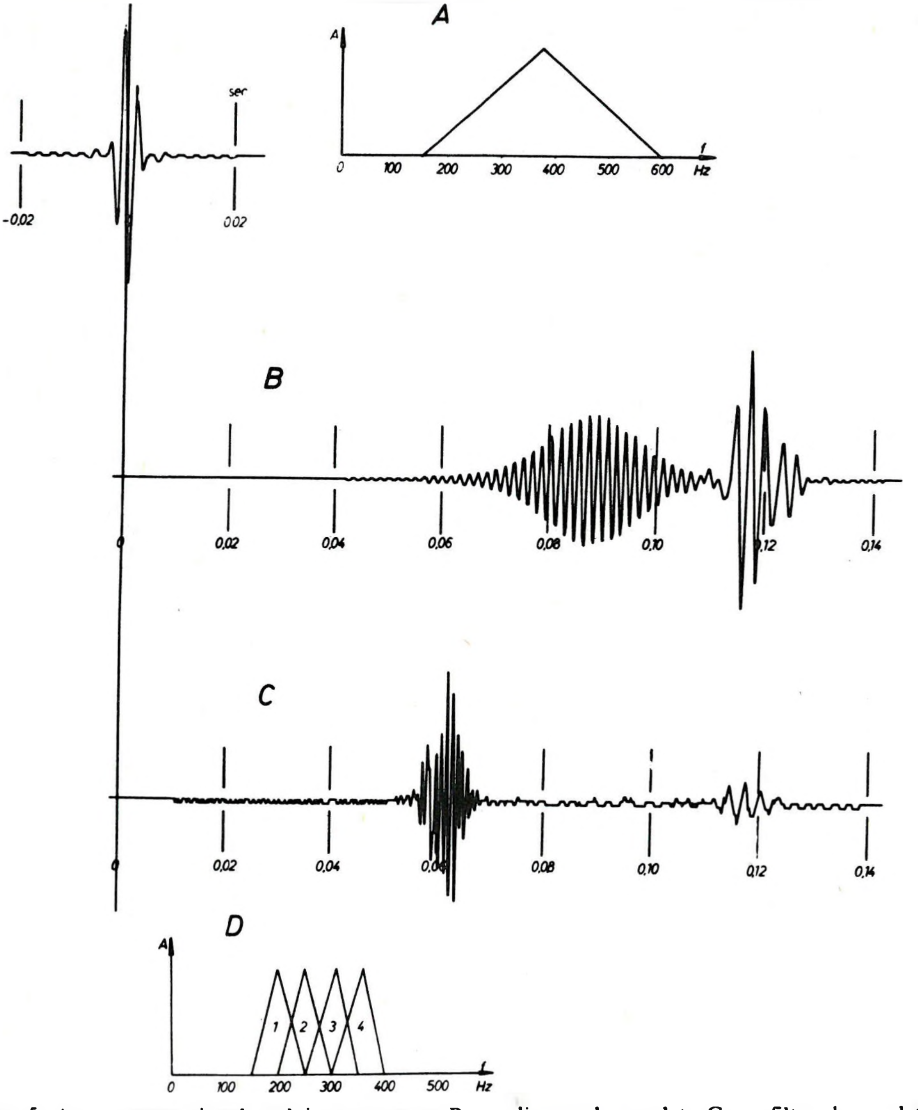

Fig. 5. A — source signal and its spectrum; B — dispersed wavelet; C — filtered wavelet; D — transfer functions of the used bandpass filters

5. ábra. A — az indulójel és spektruma; B — diszperz csatornahullám; C — szűrt csatornahullám; D — a használt sávszűrők átviteli függvényei

Фиг. 5. A – Исходный сигнал и его спектр; B – Дисперсная канальная волна; C – Отфильтрованная канальная волна; D – Частотные характеристики использованных полосовых фильтров

In *Fig. 5* the spectrum of the source signal expands from 150 to 600 Hz. The dispersed wavelet model is definitely attenuated and high amplitudes appear at its end. Four band-pass filters were used for filtering but their total width did not cover the complete signal spectrum. The main peak of the filtered wavelet indicates again the precise expected arrival time of *S* bodywaves. The wavelet is definitely recompressed in spite of the restricted bandwidth.

Figure 6 shows that the spectrum of the source signal expands from 250 to 1,000 Hz. In the first part of the dispersed wavelet model the high frequency sig-

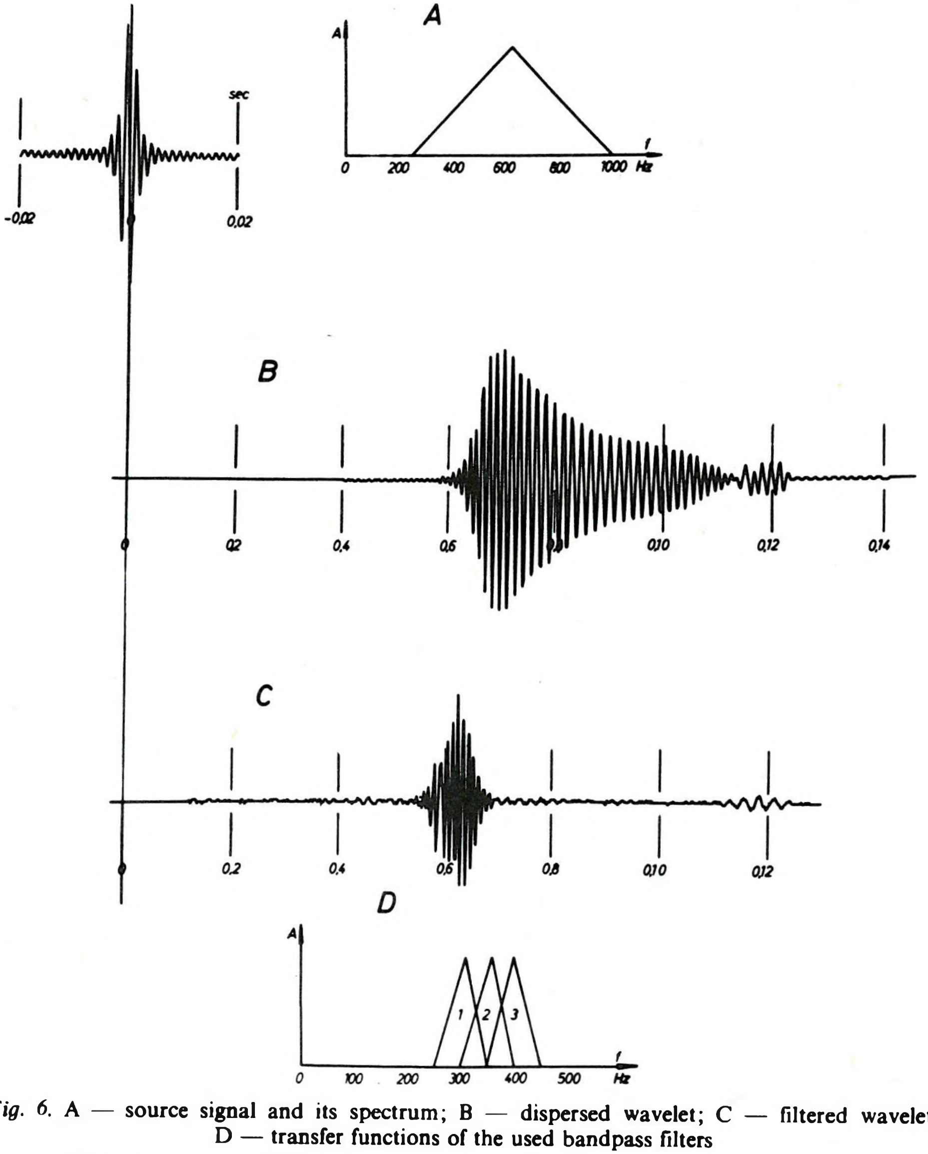

Fig. 6. A — source signal and its spectrum; B — dispersed wavelet; C — filtered wavelet; D — transfer functions of the used bandpass filters

6. ábra. A — az indulójel és spektruma; B — diszperz csatornahullám; C — szűrt csatornahullám; D — a használt sávszűrők átviteli függvényei

Фиг. 6. А – Исходный сигнал и его спектр; В – Дисперсная канальная волна; С – Отфильтрованная канальная волна; D – Частотные характеристики использованных полосовых фильтров nal has very high amplitudes whereas at the end of the wavelet the amplitudes are weak. For the filtering, three band-pass filters were used with a total bandwidth much narrower than that of the source signal. In spite of the narrow bandpass the result is satisfactory: the filtered wavelet is not more than 60% longer than the source signal.

Domain of validity

To check the validity of the above described numerical model its dispersion curves were computed and compared with the theoretical curves.

Figure 7 shows three different sets of dispersion curves: the curves of the model using calculated phase shifts (1A, 1B), the curves of the model using phase inversion instead of phase shifts (2), and the theoretical curves (3).

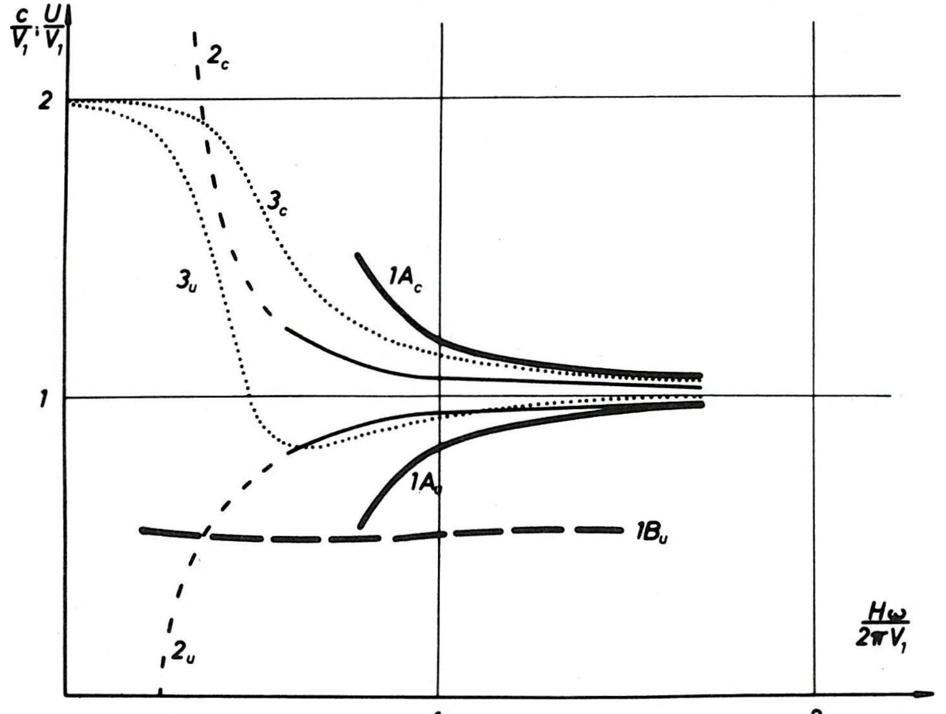

Fig. 7. Dispersion curves
1A, 1B — curves of the model using calculated phase shifts; 2 — curves of the model using phase inversion instead of phase shifts; 3 — theoretical curves

7. *ábra.* Diszperziós görbék
1A, 1B — a fázistolásokat figyelembe vevő modell diszperziós görbéi; 2 — a fázistolás helyett fázisforditásokat alkalmazó modell diszperziós görbéi; 3 — elméleti diszperziós görbék

Фиг. 7. Дисперсионные кривые
1A, 1B — модели с учетом смещений по фазе; 2 — модели, применяющей инверсию фазы вместо смещения по фазе; 3 — теоретические дисперсионные кривые

Studying the curves it can be seen that the model using calculated phase shifts produces two separated wavelets denoted by 1A and 1B. Wavelet 1A is similar to the vibration of a free plate, except for the low-frequency end of the dispersion curve which is missing because the length of the wavelet is limited by the critical angle. Wavelet 1B is a low velocity wavelet almost without dispersion. The average amplitude ratio of 1A to 1B is 20–25 dB. The two separated wavelets can be seen well in Fig. 5 (where the amplitude of wavelet 1A is attenuated because of the input spectrum), and in Fig. 6. In Fig. 4 none of the possible frequency components of wavelet 1A is present therefore here only wavelet 1B is to be seen.

The model using phase inversion corresponds to the vibration of a plate between two infinitely rigid half spaces except for the low frequency end of the dispersion curve, which is also truncated by the limited wavelet length.

Now, to answer the question of validity, one may say that wavelet 1A of the model using phase shifts gives an acceptable approximation of reality at frequencies above the ratio

$$\frac{Hf}{V_1} = 1.$$

In this frequency range wavelet 1B, which has nothing to do with reality, can be treated as background noise because of its significantly smaller amplitudes.

The model using phase inversion provides a worse approximation of the theoretical phase velocity curve, its group velocity curve fits better.

Conclusions can be drawn as follows:

— numerical models of seismic channel waves which are constructed on the basis of geometrical optics have similar characteristics to those of vibrations in a plate even if phase shifts are introduced into the model,

— similarity of the model to the vibrating plates introduces strong frequency limitations if a recompressional filter is derived from it.

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BODOKY TAMÁS, CZILLER ESZTER, KÖRMENDI ALPÁR

EGYSZERŰ ELJÁRÁS AZ SH TÍPUSÚ CSATORNAHULLÁMOK MODELLEZÉSÉRE, ILLETVE DISZPERZITÁSUK MEGSZÜNTETÉSÉRE

A dolgozat a két végtelen féltér közé ágyazott rugalmas hullámvezetőben létrejövő SH típusú csatornahullámok geometriai optikai eszközökkel történő modellezésével foglalkozik.

A bemutatott egyszerű, sugárutakra épülő modellből olyan szűrési eljárást vezet le, amellyel a diszperz SH típusú csatornahullámok közelítően nem diszperz, impulzusszerű jellé alakíthatók. Befejező részében vizsgálja a modell diszperziós görbéit, majd összehasonlítva ezeket az elméleti görbékkel, meghatározza a bemutatott modellezési és szűrési eljárások érvényességi tartományát. A tárgyalt témát a szénbányákban végzett telephullám-szeizmika terjedése és feldolgozási problémái teszik időszerűvé.

Т. БОДОКИ, Э. ЦИЛЛЕР, А. КЁРМЭНДИ

ПРОСТОЙ СПОСОБ ДЛЯ МОДЕЛИРОВАНИЯ КАНАЛЬНЫХ ВОЛН ТИПА SH И ДЛЯ УСТРАНЕНИЯ ИХ ДИСПЕРСИИ

В работе обсуждаются вопросы моделирования при помощи средств геометрической оптики канальных волн типа SH, возникших в упругом волноводе, залюченном между двумя бесконечными полупространствами.

По изложенной простой модели, построенной на траекториях, выводится способ фильтрации, при помощи которого дисперсные канальные волны типа SH преобразуются в приблизительно недисперсные импульсные сигналы. В заключении рассматриваются дисперсионные кривые модели, затем сопоставив их с теоретическими кривыми, определяется диапазон действия приведенных способов моделирования и фильтрации.

Актуальность обсуждаемой темы вызывают распространение сейсморазведки с использованием пластовых волн в угольных шахтах и проблемы обработки получаемых данных.