NUMERICAL MODELLING OF SEISMIC WAVE FIELDS IN MODELS CONTAINING STACKS OF THIN LAYERS

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Резюме: *Изучаются возможности численного моделирования высокочастотных сейсмических волновых полей в горизонтально-неоднородной слоистой среде с пачками тонких слоев. Показывается что очень удобным для численного моделирования является комбинация метода суммирования гауссевых пучков и метода матричного (Томпсон-Гаскел, или его модификации). Метод суммирования гауссевых пучков используется в тольстых слоях и матричный метод применяется локально к пачкам тонких слоев. Приведены численные примеры расчетов для упрощенной модели тонкого переходного слоя между двумя полупространствами. Некоторые интересные свойства волн отраженных от простой границы раздела и от переходного слоя обсуждаются из сейсмологической точки зрения.*

Summary: *The possibilities of numerical modelling of high-frequency seismic wave fields in laterally varying layered structures containing stacks of thin layers are discussed.It is shown that the hybrid code based on the combination of the Gaussian beam summation method and of the matrix method (Thompson-Haskell, or other) may be very suitable for this purpose. The Guassian beam summation method is applied to thick smooth layers and the matrix method is locally applied to stacks of thin layers. Numerical examples for a simplified model of a transition layer between two halfspaces are shown. Certain interesting properties of waves reflected from a single interface and from a transition layer are discussed from the seismological point of view. Considerable attention is devoted to converted reflected waves.*

1. INTRODUCTION

High-frequency asymptotic methods have been recently used to evaluate seismic wave fields in general, two-dimensional and three-dimensional, structures. High-frequency methods are especially suitable for models consisting of thick layers, in which the velocity and density varies slowly, and which are separated by smooth interfaces of the first order. For a detailed exposition of various applications of the ray method and of the method of summation of Gaussian beams refer to [4, 5].

In seismic prospecting and seismology, it is often necessary to consider models, in which certain thick layers are separated by stacks of thin layers, instead of interfaces of the first order. The ray method and the Guassian beam method may, in principle, be applied even to such situations, but the number of rays would be extremely large and the algorithms and computations very cumbersome. The waves propagating in such models will have a strongly interferential character. The properties of interference waves will be quite different from those of the individual elementary waves which form them. Moreover, the accuracy of the computations of interference waves by summing ray contributions is only limited. In case of a destructive interference, the ray contributions may cancel each other and the wave field will be formed by non-ray or by higher-order ray contributions, which are not usually considered in the computational algorithms.

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It would be useful to apply algorithms which evaluate the wavefield of interference waves in stacks of thin layers as a whole, not separated into individual waves. In vertically inhomogeneous media, where the velocity depends only on depth, the well-known reflectivity method can be used to perform such computations, see [11]. In laterally varying media, however, the reflectivity method cannot be used. In these media, the stacks of thin layers complicate considerably the evaluation of synthetic seismic wave fields. Some general approaches proposed in [12] are very promissing, but their practical application to the problem under consideration will take some time. Generally, it would be possible to use methods of finite differences of finite elements, but the computation for larger models would be very expensive. For three-dimensional models, the computer time and memory requirements would be perhaps too large even for the currently fastest computers.

It may be suitable to apply some *hybrid methods* to solve the problem of seismic wave propagation in media with stacks of thin layers. Several hybrid methods have been proposed in the literature. Well-known is namely the combination of the ray method and the matrix method proposed by Ratnikova [16]. Ratnikova assumes a one-dimensional medium, in which the velocities and densities are only depth-dependent. The model consists of thick layers, in which the velocities and density vary only slowly with depth, separated by interfaces of the first order and/or by thin transition layers, formed by stacks of thinner homogeneous layers. The changes of velocities and density within the transition layers may be arbitrary (laminated layers, etc.). The procedure proposed and used by Ratnikova is as follows: The ray theory is applied to thick layers with smooth changes of velocity. This means that the ray theory is applied to a fictitious model which is composed of thick layers only; the thin transition layers being excluded. Then the reflection/transmission coefficients at certain interfaces are replaced by the frequency dependent reflection/transmission coefficients for the relevant thin transition layers. The reflection/transmission coefficients may be evaluated by various well-known matrix methods, such as the Thompson-Haskell method, the method of delta matrices, etc. Note that the travel time corrections corresponding to the transmission through the transition layers is automatically included in the transmission coefficients. The justification of the above method is based on the method of stationary phase, see also [9]. The assumption used in the stationary phase method is that the reflection/ /transmission coefficients vary only slowly as a function of the angle of incidence.

As the method of Ratnikova has been applied to an one-dimensional medium with depth-dependent parameters only, it represents only an approximate substitute of the reflectivity method. In comparison with the reflectivity method, it has certain advantages and disadvantages. The principal disadvantage consists in its limited accuracy. The accuracy of the method has been investigated by several authors, mainly by comparing its results with the reflectivity method. The best accuracy is obtained for very thin transition layers (in comparison with the prevailing wavelength) and for subcritical reflections. The accuracy decreases with increasing thickness of stacks of layers and for critical and overcritical reflections. The main advantages of the method consist in its computational efficiency, in simple identification of the individual phases (waves), and in its simple generalization for laterally varying media.

Note that the frequency-dependent reflection/transmission coefficients automatically include all multiply reflected (possibly converted) waves within the stacks of thin layers. Thus, the number of elementary waves which must be considered in the evaluation of the synthetic seismic wave field is reduced drastically. Even more, the frequency-dependent reflection/transmission coefficients include certain non-ray inhomogeneous waves, such as tunel waves.

A similar hybrid method can also be obtained by combining the Gaussian beam summation approach with the matrix method. Similarly as in the preceding case, we again assume that the model consists of thick layers with a smooth distribution of velocity separated by thin transition layers. The Gaussian beam approach is applied to thick layers only, and the transition layers are taken into account using the relevant frequency-dependent reflection/transmission coefficients.

The main aim of the present investigation is to modify the existing program packages for 2-D and 3-D media, based on the ray method and on the Gaussian beam method, for media with stacks of thin layers. The first attempts to solve this problem in its full complexity are described in [7], including some examples of numerical computations for laterally varying structures. This paper reports the preliminary results of a considerably simpler problem — the hybrid combination of the Gaussian beam and matrix methods for one stack of thin layers only. Several numerical examples, which are of some seismological interest, are shown and discussed.

2. THEORY

The theory of the ray method and of the Gaussian beam summation method is well described in several papers and books. For the basic principles of the ray method refer to [8]. The complete theoretical treatment of both methods for 3-D laterally varying layered structures can be found in [6]. All these references deal with models consisting of thick layers with a smooth velocity distribution separated by smooth interfaces of the first order. For simplicity, we shall assume that the interfaces do not intersect and/or touch other interfaces. We shall call such a model the "original model", or the "old model". To shorten this article, we shall not present here the relevant equations. We shall only notice that these equations contain standard plane wave reflection/transmission coefficients at the individual reflection/transmission points, at which the ray under consideration is incident at the interfaces.

Let us now consider a new model, in which certain interfaces of the first order are replaced by transition layers of a constant thickness. By a transition layer of a constant thickness we understand a layer which has a constant vertical thickness, not a normal thickness; the normal thickness depends on the dip of the layer. Such layers may be simply introduced into the laterally varying model or removed from it, changing only the vertical dimension of the model.

The ray tracing, dynamic ray tracing, etc., in the new model may be simply performed in the same way as in the old model (without stacks of thin layers). For transmitted rays, the initial point of the transmitted ray is situated on the other side of the transition layer, at the normal to the layer passing through the point of incidence.

The spreading free amplitudes are evaluated in the same way as in the old model (with interfaces of the first order); only the proper frequency dependent reflection/transmission coefficients at the transition layers are used instead of standard reflection/transmission coefficients. Note that the structure within the thin transition layer may depend arbitrarily on depth. It may, however, also vary smoothly in the horizontal direction. The only limitation is that the vertical thickness of the whole stack is small and remains fixed. In the evaluation of reflection/transmission coefficients, the local normal thickness must be considered as the thickness of the layer. In this way, the computational thickness of the transition layer varies from place to place, depending on the dip of the transition layer.

To evaluate the reflection/transmission coefficients for the transition layer, the layer is simulated by a stack of very thin layers. The well-known matrix methods may then be used to evaluate the reflection/transmission coefficients. Various matrix methods are presently at our disposal. The best known is the Thompson-Haskell method. The method is based on the successive multiplication of 4×4 layer matrices. Instead of 4×4 matrices, the 6×6 or 5×5 delta matrices may also be used. The relevant theoretical expressions can be found in [3, 10], where other references are given. The layer matrices may also be substituted by "interface matrices", consisting of standard reflection/transmission coefficients. For details see [1, 12, 15]. Various matrix formulations generally lead to the same results, but may differ in accuracy in certain situations. This problem will not be investigated here.

3. NUMERICAL TESTS

In this paper, we shall consider the simplest possible model to which the proposed hybrid method can be applied, i.e. the stack of thin layers between two homogeneous isotropic perfectly elastic halfspaces. The Gaussian beam solution for the model without the stack of thin layers is described in detail in [13, 14], where all the necessary equations are given. The above papers also describe the relevant single purpose program GB, based on the summation of Gaussian beams, designed for the numerical modeling of reflected and transmitted wave fields generated at the plane interface, and discuss the results of computations. The results are also shortly summarized in [5].

Program GB was modified to take into account the stack of thin layers between the two halfspaces. In other words, the routine evaluating the standard reflection/ /transmission coefficients at a plane interface between two halfspaces was replaced by the routine REFLEX which evaluates the reflection/transmission coefficients in a stack of thin layers between two halfspaces.

The routine REFLEX was written in 1972 by the second named author to investigate the spectral properties of reflected waves from transition layers. It is based on the Thompson-Haskell approach, i.e. on the multiplication of 4×4 layer matrices. The accuracy of the routine was sufficient for our purposes.

Two models are considered: Model SHARP INTERFACE and model TRANSITION LAYER.

Model SHARP INTERFACE consists of two halfspaces separated by a plane first-order interface. In the first, upper halfspace, the P- and S-velocities and the density are 6·4 km/s, 3·7 km/s and 2 980 kg m^{-3} respectively. In the second halfspace, the same parameters are as follows: 8 km/s, 4·62 km/s, 3 300 kg m^{-3}.

Model TRANSITION LAYER: A transition layer of 1 km thickness is introduced between the two halfspaces of model SHARP INTERFACE. The velocity of P waves in the transition layer increases linearly from 6·4 km/s to 8 km/s. Similarly, the S wave velocities change linearly from 3·7 km/s to 4·62 km/s and the densities from 2 980 kg . . m^{-3} to 3 300 kg m^{-3}.

The point source with an isotropic radiation pattern of *P* and *S* waves is situated in the upper halfspace, at a distance of 30 km from the interface in the model SHARP INTERFACE, and at a distance of 29·5 km from the upper boundary of the transition layer in model TRANSITION LAYER. The amplitudes of *P* and *S* waves generated by the source are assumed to be the same. The receivers are situated on a line parallel with the interface (or with the transition layer) passing through the source.

The wavefield of reflected waves in the neighbourhood of the critical point and the wavefield of head waves is influenced by the initial parameters of Gaussian beams used in the expansion. It was shown by Konopásková and Červený [13, 14] that the Gaussian beam summation method yields sufficiently accurate results if the Gaussian beams used in the expansion are sufficiently broad. In our test examples, the parameters of Gaussian beams are specified at the endpoints of rays along the profile of receivers as follows: the phase front at the endpoint is plane, the half-width L_0 of Gaussian beams at the endpoints is constant, independent of rays. For *PP* and *PS* waves, $L_0 = 85{\cdot}7$ km. Similarly, for *SS* and *SP* waves, $L_0 = 65{\cdot}1$ km. In this way, very broad Gaussian beams are considered. This guarantees the high accuracy of the computations, at least for model SHARP INTERFACE. The high accuracy is, of course, paid for by longer computer time, which is required in case of broad beams.

The parameters controlling the expansion of the wave field into Gaussian beams and of the windowing of Gaussian beams are selected in such a way as to avoid introducing additional errors into the computations. The ray diagram was sufficiently dense (more than 400 rays were evaluated). The Gaussian beams are windowed in the following way: The contribution of individual Gaussian beams is neglected at distances from the central ray of the beam at which the amplitude is 0·1 times smaller than the amplitude on the central ray.

All the computations are performed in the frequency domain. The frequency dependent amplitude-distance curves are presented for frequencies $f = 4$ Hz and $f = 10$ Hz. By amplitude we understand the amplitude of the vertical component of the displacement vector.

In practical application, it is assumed that the hybrid Gaussian beam – matrix method will be used for thin transition layers, the thickness of which does not exceed λ, where λ is the prevailing wavelength of the incident wave. In test examples presented here we choose the thickness of the transition layer even larger, to emphasize the possible effects of the transition layer. For frequency $f = 4$ Hz, the wavelength of the incident *P* wave is 1·6 km, and of the incident *S* wave 0·92 km. For frequency $f = 10$ Hz, the wavelength of the incident *P* and *S* wave is 0·64 km and 0·37 km, respectively.

The frequency-dependent amplitude-distance curves for frequencies 4 Hz and 10 Hz, for the reflected waves of the *PP*, *PS*, *SP* and *SS* type, are shown in Figs. 1–4. These figures are discussed in the next section. See also [2].

4. DISCUSSION OF RESULTS

From a computational point of view, the numerical tests proved that the hybrid Gaussian beam – reflectivity algorithm does not introduce any numerical problems, instabilities, etc. The computer time for the transition layer model is, of course, considerably longer than for the sharp interface model. This was, however, expected, as the evaluation of the frequency-dependent reflection/transmission coefficients for a stack of thin layers is considerably more time consuming than for a single interface of the first order.

Certain results of test computations are interesting even from the seismological point of view. The Gaussian beam computations remove the singularities of the ray method in the critical regions, in regions where the ray amplitudes vanish, etc. It is very interesting to compare the amplitudes of the waves reflected from the sharp interface and from the transition layer. In our discussions, we shall pay attention not only to *PP* reflected waves, but also to *SS* reflected waves and to *PS* and *SP* converted reflected waves. To shorten the discussions, we shall call the waves reflected from the sharp interface SI reflections, and the waves reflected from the transition layer, TL reflections.

4.1 *PP* reflected waves

First we shall consider the amplitudes of the vertical component of the *PP* reflected waves (*P* incident, *P* reflected), see Fig. 1. Note that the refraction index $n = \alpha_1/\alpha_2 = 0{\cdot}8$ and that the critical point of the *PP* reflected wave is situated at the epicentral distance of 80 km. Beyond the critical point, the head wave *PPP* also exists and is automatically included in the *PP* reflected wave field.

The amplitude-distance curve of the SI reflection has a well-known shape. The amplitudes first smoothly decrease with epicentral distance, are minimum at about 50 km, and then increase again. They do not reach maximum at the ciritical distance of 80 km, as would follow from the ray theory, but at some distance beyond it. The position of the maximum is frequency dependent. For $f = 4$ Hz, the maximum is situated approximately at 100 km, for $f = 10$ Hz at a distance of 93 km. The oscillations beyond the maximum are due to head waves PPP which are generated beyond the critical point.

Let us now discuss the differences between the SI and TL reflections. The most dominant diferences can be observed at subcritical distances; the amplitudes of TL reflections are considerably smaller than the amplitudes of SI reflections there. They are generally the smaller, the higher the frequency. For higher frequencies (see Fig. 1), some oscillations appear in the amplitude-distance curves of TL reflections even at subcritical distances. The oscillations are caused by the mutual interference of waves reflected from the upper and lower boundaries of the transition layer and of multiply

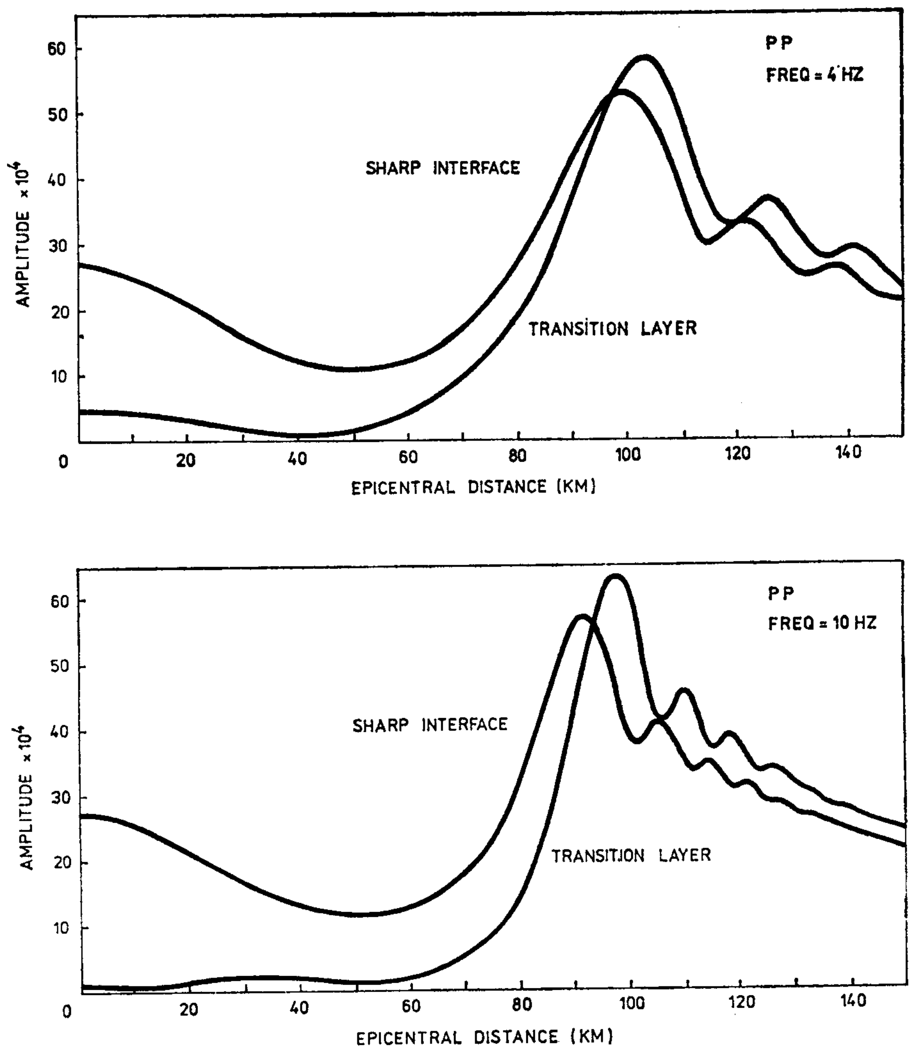

Fig. 1. The amplitude distance curves of *PP* waves reflected from a sharp interface and from a linear transition layer, 1 km thick. The point source and the receivers are situated 30 km from the sharp interface, or 29.5 km from the upper boundary of the transition layer, on a line parallel to the interface. The vertical component of the displacement vector is considered. The waves reflected from the sharp interface are evaluated by the Gaussian beam summation method, the waves reflected from the transition layer by the hybrid Gaussian beam summation-reflectivity method.

reflected waves inside the transition layer. These oscillations depend on the form of the transition layer and on the frequency.

The differences between the SI and TL reflections are not so dominant at overcritical distances. The maximum of the amplitude-distance curve is shifted to slightly larger epicentral distances for TL reflections. Similarly, the oscillations caused by head waves are slightly larger for the TL reflections than for the SI reflections. This means that the amplitudes of head waves are slightly larger in case of the transition layer than in the case of the sharp interface.

4.2 *PS* converted reflected waves

Now we shall consider the amplitudes of the vertical component of the *PS* converted reflected waves (*P* incident, *S* reflected), see Fig. 2. The critical point is situated at the epicentral distance of 56 km. Beyond the critical point, the head wave *PPS* also exists and is automatically included in the *PS* reflected wave field.

Generally speaking, the amplitudes of converted *PS* waves are considerably smaller than the amplitudes of *PP* reflected waves, with some exception of epicentral distances close to 60 – 70 km, where both amplitudes are approximately the same. Amplitudes of *PS* converted waves may be even slightly larger there than the amplitudes of *PP* waves.

The *PS* waves reflected from the sharp interface are zero at zero epicentral distance. They increase smoothly with epicentral distance and reach their maximum at about 35 km. Then they decrease and reach a minimum at about 52 km. In the ray approximation, the amplitudes vanish at a distance close to 50 km. The Gaussian beams, however, do not yield zero amplitudes there, but a smooth minimum at this distance. In the critical region, the amplitudes smoothly increase and reach their maximum at a distance of about 75 km. The oscillations beyond this maximum are due to *PPS* head waves (which propagate as *P* waves under the interface.)

The amplitudes of TL reflections are considerably smaller than the SI reflections everywhere, not only at subcritical distances, but also at overcritical distances. This is the large difference in comparison with the *PP* reflected waves. The amplitudes depend considerably on frequency; they are the smaller, the higher the frequency. For higher frequencies (see Fig. 2), some minima of interferential character again appear at subcritical distances.

In our computations, the amplitude of the vertical component of the displacement vector of the *PS* converted TL reflected wave vanishes under normal incidence, see Fig. 2. This result corresponds to the ray method. It can also be confirmed by exact computations (finite differences, reflectivity method, etc.), but only for high H/λ, where H is the distance of the point source from the interface and λ the wavelength of the *P* wave. For H/λ close to unity or even smaller, exact methods predict non-zero amplitudes. This result can also be obtained by the summation of Gaussian beams, if H/λ is small. In our case, however, H/λ is larger than 15, so that the normal incidence vertical amplitudes of *PS* waves cannot be observed.

The amplitudes of the displacement vector of the *PS* converted reflected wave under normal incidence should strictly vanish in the horizontal component.

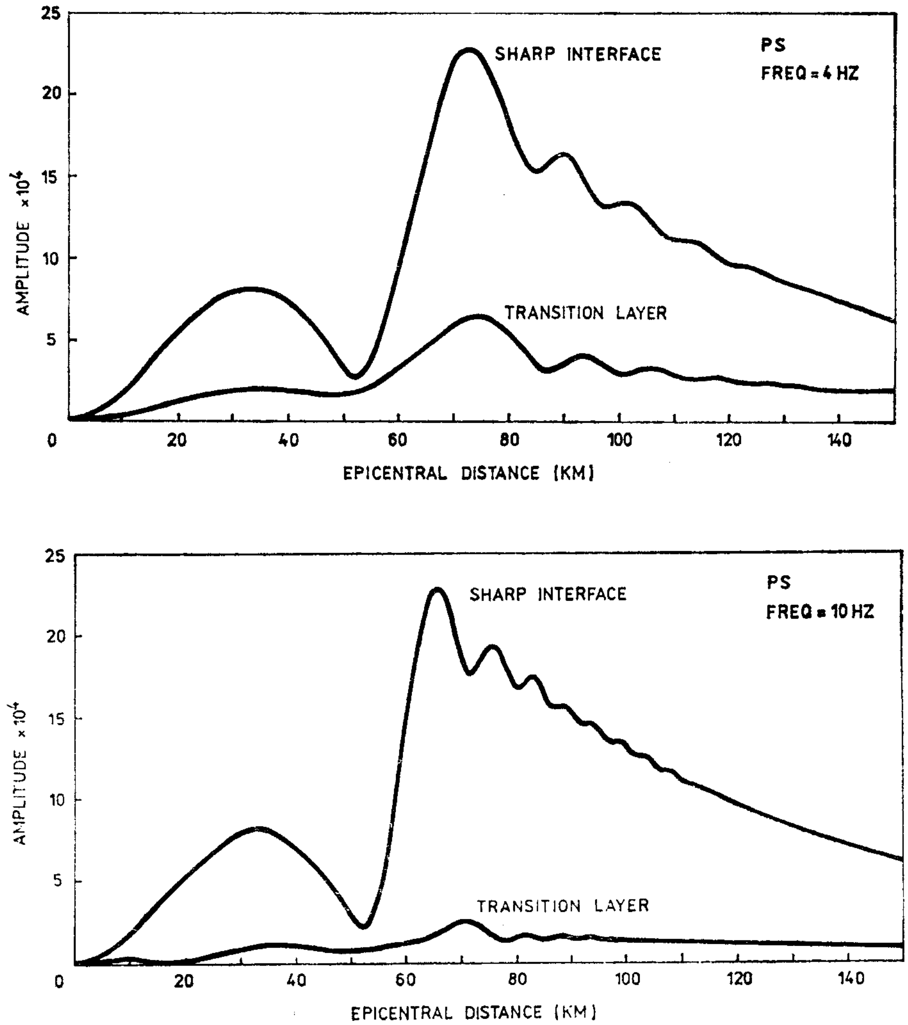

Fig. 2. The same as in Fig. 1, for *PS* converted reflected waves.

This conclusion follows simply from some symmetry considerations. In our computations, principal attention was devoted to larger offsets (critical regions, etc.), not particularly to the zero offset. For this reason, the Gaussian beams were not shot quite symmetrically to positive and negative distances, but primarily to the positive distances. The number of Gaussian beams shot to the left of the source was limited to a certain region close to the zero offset only. This asymmetry in the summation of Gaussian beams introduced some small errors in the amplitudes close to the zero offset: non-vanishing amplitudes of *PS* converted waves at the horizontal component. See Fig. 2.

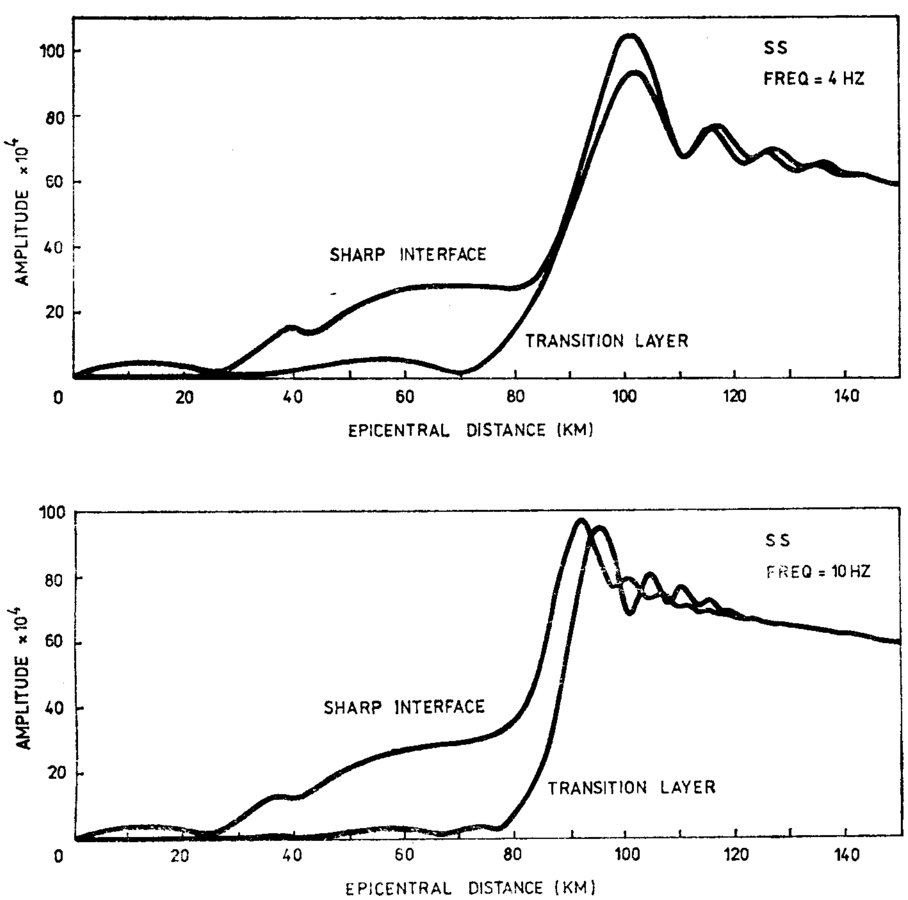

Fig. 3. The same as in Fig. 1, for *SS* reflected waves.

4.3 *SS* reflected waves

The amplitude-distance curves of *SS* reflected waves (*S* incident, *S* reflected) are rather complicated, see Fig. 3. The *SS* wave has three critical points. The most pronounced anomalies in the amplitude-distance curves are connected with the critical point at 80 km. Beyond this critical point, head waves *SSS* also exist, see the strong oscillations in the amplitude-distance curves. The two other critical points are situated at smaller epicentral distances. The first of them is situated at 31 km. Beyond it, head waves *SPS* exist. These head waves have a *P* element of the ray below the interface. The next critical point is at 43 km and is connected with the anomalous head waves *SPS*, with a *P* element of the ray above the interface (in the first halfspace). Both *SPS* head waves are, however, very weak; they do not cause pronounced oscillations in the amplitude distance curves.

The main maximum of the amplitude-distance curves of *SS* waves is situated approximately at the same epicentral distance as the maximum of the amplitude-distance curve of *PP* waves. Beyond this maximum, the behaviour of *SS* and *PP* reflected waves is very similar. For smaller epicentral distances, however, the amplitudes of *SS* waves are considerably more complicated. The complications are due to the two additional critical points in that region, and even with one point of zero ray amplitude close to 27 km. The Gaussian beam summation approach does not yield a zero amplitude at this distance, but only some smooth minimum. Generally, the amplitudes of *SS* waves vanish at zero epicentral distance and are very small at small epicentral distances of less than 30 km. At intermediate epicentral distances (30 – 90 km), the amplitudes are higher; they reach about $\frac{1}{3}$ of their maximum values.

For a transition layer, the amplitudes beyond the main maximum at 90 – 100 km are again approximately the same as for the SI interface. At smaller epicentral distances (less the 80 km), the TI amplitudes are considerably smaller than the SI amplitudes and depend on frequency. They practically vanish at distances of less than 30 – 40 km.

4.4 *SP* converted reflected waves

The amplitude-distance curves of the vertical components of the *SP* converted reflected waves (*S* indicent, *P* reflected) are shown in Fig. 4. The *SP* waves have one critical point, situated at the epicentral distance of 56 km. Beyond this critical point, head waves *SPP* are formed.

Beyond epicentral distances of 80 km, the amplitudes of the vertical component of SP waves are considerably smaller than the amplitudes of the vertical component of *SS* waves. At smaller epicentral distances, the situation is more complicated. At distances of less then 30 km, the amplitudes of *SP* waves are larger than the amplitudes of *SS* waves. For a mutual comparison, see also Fig. 6, which will be discussed in greater detail later.

For a normal incidence (zero epicentral distance), the amplitudes of *SP* waves do not fully vanish in Fig. 4. This is, however, caused by the fact that the Gaussian beams were not shot quite symmetrically around the zero offset. For a more detailed discussion see Section 4.2.

The SI amplitude-distance curves of *SP* converted waves have two pronounced maxima, at about 20 km and 60 – 70 km. The position of the second maximum is frequency dependent, as it corresponds to the critical region. Beyond the second maximum, the oscillations show the existence of *SPP* head waves. They are not too pronounced, so that the amplitudes of the *SPP* head wave are not too large.

In case of the transition layer, the amplitudes of *SP* converted waves are considerably smaller than the SI amplitudes in the whole range of epicentral distances. The TL amplitudes depend considerably on frequency, they decrease with increasing

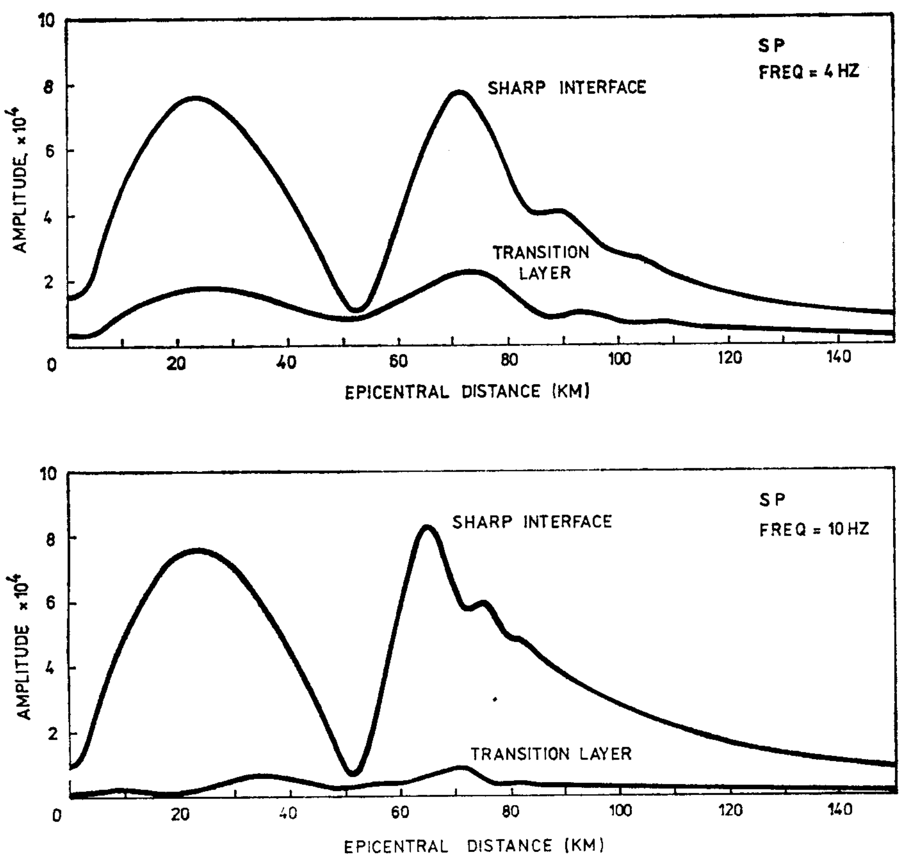

Fig. 4. The same as in Fig. 1, for *SP* converted reflected waves.

frequency everywhere (see Fig. 4). It is, however, interesting to observe that the amplitudes of *SP* converted waves do not vanish at zero offset even in case of the transition layer.

4.5 Mutual comparison of amplitudes of individual waves

As the amplitude-distance curves presented in Figs. 1 – 4 correspond to the vertical component only and are plotted on different scales, a straightforward mutual comparison of the actual amplitudes of the individual waves cannot be made. For this reason, we present Figs. 5 and 6, which show both the vertical and horizontal components of the displacement vector of individual reflected waves, and use the same scale. Figure 5 corresponds to the source of a *P* wave, Fig. 6 to the source of an *S* wave. To limit the number of figures, we only consider the frequency of 4 Hz and

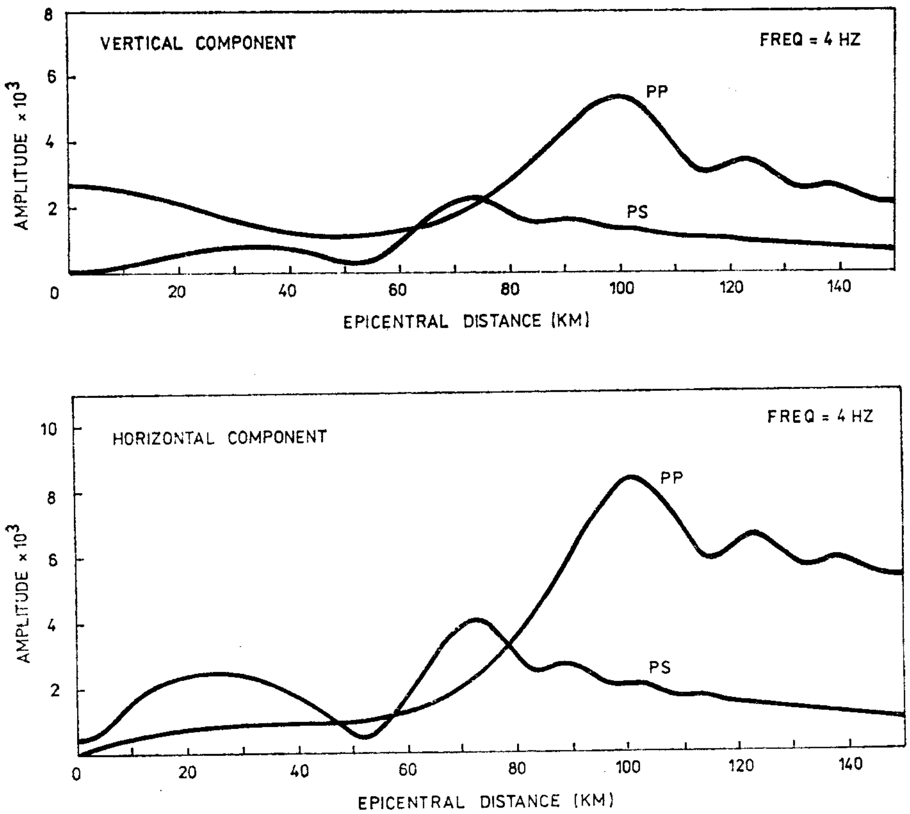

Fig. 5. The amplitude-distance curves of *PP* and *PS* waves reflected from a sharp interface. The point source and receivers are situated 30 km from the interface.

the sharp interface. (The relation between the amplitudes for the SI and TL reflections remains the same for the horizontal component as for the vertical component, see Figs. 1–4.)

The figures are self-explanatory. We shall only shortly discuss the mutual relation of the individual waves at smaller epicentral distances. We can again see that the amplitudes of converted waves are surprisingly strong in several cases. In the horizontal component, the *PS* reflected wave is stronger than the *PP* reflected wave at epicentral distances of 0 to 80 km (with some exception close to 50 km). A similar effect for the vertical components of *SP* and *SS* waves can also be observed: the *SP* converted wave is stronger than the *SS* reflected wave at epicentral distances of 0 to 30 km. This effect was briefly discussed in Section 4.4.

Note that the small non-zero amplitudes of the horizontal component of the *PS* wave and of the vertical component of the *SP* wave at zero epicentral distance are not realistic, but are caused by numerical effects explained in detail in Section 4.2.

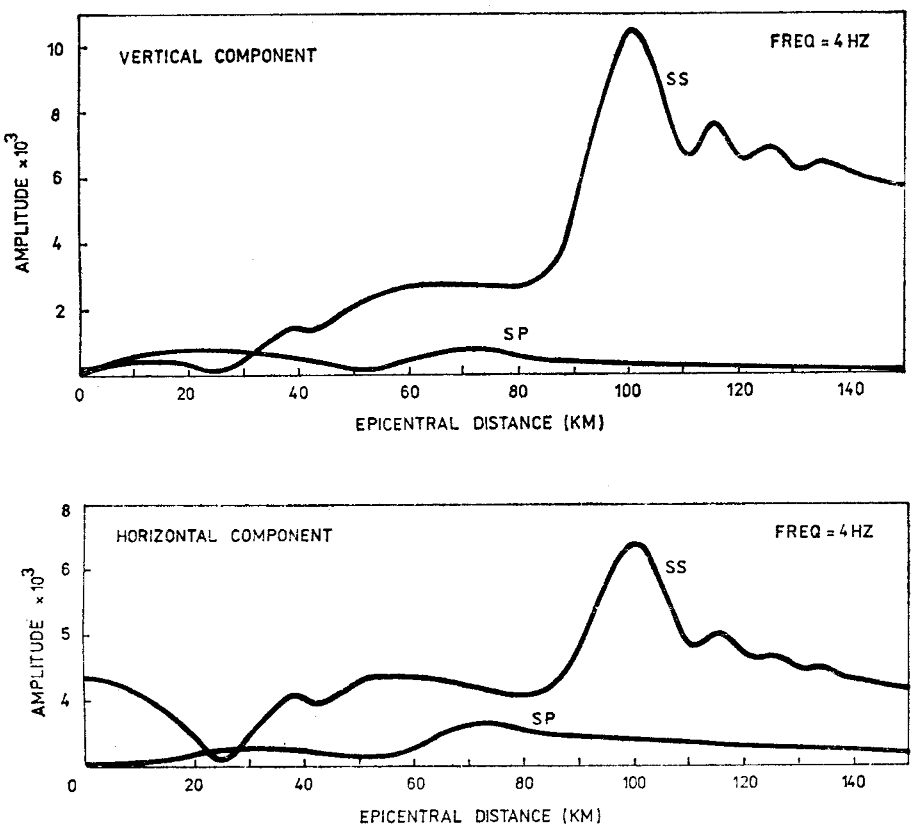

Fig. 6. The same as in Fig. 5, for *SS* and *SP* reflected waves.

5. CONCLUSIONS

It was shown that the hybrid code based on the combination of the Gaussian beam summation method with the matrix method can be simply applied in the numerical modelling of high-frequency seismic wave fields in models consisting of thick layers containing some stacks of thin layers. The application of the Gaussian beam summation method instead of the ray method in this hybrid code has many advantages. The main advantage consists in the higher accuracy of the Gaussian beam summation method in the singular regions of the ray method (caustics, critical regions, etc.). Another advantage is that the Gaussian beam does not require two-point ray tracing, only initial value ray tracing being necessary. This makes the hybrid code with the Gaussian beams more flexible and computationally efficient. Finally, the Gaussian beam summation method automatically yields some weighting of the frequency-dependent reflection/transmission coefficients from stacks of thin layer in the vicinity of the point of incidence. Such weighting is involved even in more accurate methods, such as the reflectivity method, but is not involved in the standard ray method.

The proposed hybrid code will be used to produce more general program packages for the numerical modelling of high-frequency seismic wave fields in laterally varying layered models including stacks of thin layers. A detailed description will be given elsewhere. Independently, the accuracy of the method will be studied by comparison with more accurate methods for simpler types of media, mainly with the reflectivity method.

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