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(54) **Tunnel-structure to suppress propagation of pressure disturbances generated by travelling of high-speed trains.**

(57) A tunnel-structure for travelling of high-speed trains is claimed wherein propagation of pressure disturbances generated by the train can be suppressed and especially emergence of acoustic shock waves can be avoided. This structure consists of the main tunnel for the trains and of many cavities arranged in the outside of the tunnel and in array axially with each cavity connected to the tunnel through a connecting passage(s).

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FIELD OF THE INVENTION

The present invention relates to tunnel-structure so that propagation of pressure disturbances generated by travelling of high-speed trains can be suppressed and especially emergence of acoustic shock waves can be avoided.

PRIOR ART

It is likely that high-speed trains in future must travel inside of a tunnel, namely a tubular passage in general, because of the environmental noise problem and the weather problem. Pressure disturbances generated by travelling of trains are propagated along a tunnel in the form of sound. Then as the tunnel plays a role of a waveguide for sound, they are transmitted far down without any geometrical spreading. While their intensity depends crucially on the ratio of a train's cross-sectional area to a tunnel's one, the faster the train travels, the more intense sound is generated. Thus there will arise new noise problem in the tunnel associated with propagation of the so-called nonlinear acoustic waves.

Even at present, when the high-speed train (Shinkansen) rushes into the tunnel, indeed, there happens the burst tone at the other end of the tunnel. As the train's speed becomes high, this problem would become severer unless suitable measures were taken. Thus it may be projected that the magnetically levitated trains will travel inside of tunnels as much as possible. In fact, the test line now under way is to be constructed almost in the tunnels over the line of 40km long. When the magnitude of pressure disturbances becomes high in such a long tunnel unprecedentedly, profiles of pressure disturbances tend to be steepened due to the nonlinearity to lead eventually to emergence of shock waves unexpectedly far down the tunnel, even if the train's speed is well below the sound speed. Emergence of the shock waves will give rise not only to severer noise problem but also to deterioration in performance and durability of the trains as well as the tunnels.

For reduction of this problem, it is essential to lower the ratio of the train's cross-sectional area to the tunnel's one. This ratio is set to be 21% for the Shinkansen, while for the magnetically levitated trains, it is lowered to be 12%. The smaller value of this ratio means the larger tunnel's cross-sectional area and also the higher cost in construction. The present invention makes it possible to suppress propagation of pressure disturbances generated by travelling of high-speed trains even in a tunnel of smaller cross-sectional area and especially to avoid emergence acoustic shock waves.

SUMMARY OF THE INVENTION

The tunnel structure claimed by this invention consists, as shown in Fig.1, of the main tunnel **1** for the trains and of many cavities arranged in the outside of the tunnel and in array axially with each cavity **2** connected to the tunnel through a passage **3**. Here the cavity is not necessarily a sphere and both axes of the tunnel and the passage are not necessarily normal each other. Also the passages may be positioned arbitrarily around the periphery of the tunnel. Technically, the above structure is realizable as shown in Fig.2 by arranging a side tunnel **4** in parallel with the main one and partitioning it by a bulkhead **5** into compartments as a cavity, which are connected to the tunnel through passages. But the axial spacing between the neighbouring resonators should be taken much smaller than a characteristic wavelength of the pressure disturbances. This requirement is satisfied in the far field because the characteristic wavelength there is determined by the train's axial length so that the pressure disturbances are propagated as an infrasound. As an extension, two tunnels can share the one side tunnel **4** as shown in Fig.3, connected by the passages with suitable dampers or bulk heads **6**. In addition, if different kinds of the array are connected, the effect of suppression of propagation of pressure disturbances is enhanced significantly. As shown in Fig.4, for example, the cavities **7** and **8** of different volume are connected through the passages **9** and **10** of different size with each axial distance. This double array can be realized as shown in Fig.5 without arranging two side tunnels by partitioning the one side tunnel **11** into compartments **12** of two different volume with the passages **13** of two different cross-sectional area.

One unit of the cavity and the connecting passage constitutes the resonator. If its natural frequency is chosen to be near to the characteristic frequency of the pressure disturbances, it is expected that their energy is absorbed in the resonators. By arranging many resonators in array, this effect will be enhanced. But what is to be emphasized is that the array of resonators does not only decay the propagation of pressure disturbances by absorbing their energy but also make their propagation velocity dependent of the frequency. In other words, the array introduces the dispersion into acoustic waves. It is this dispersion rather than the dissipation due to the absorption of energy that can suppress emergence of shock waves by

'dispersing' high frequency components generated by the nonlinearity in the course of propagation.

For this end, there arises an important problem as to how to design the array suitably. For identical cavity and passage connected with axially equal spacing, it is shown that the effect of the array of resonators is controlled by two parameters called the 'coupling parameter' κ and the 'tuning parameter' Ω defined, respectively, by

$$\kappa = \frac{V}{2\epsilon A d} \quad \text{and} \quad \Omega = \left(\frac{\omega_0}{\omega}\right)^2,$$

where V , A and d denote, respectively, the cavity's volume, the tunnel's cross-sectional area and the axial spacing, $\epsilon = \{[(\gamma + 1)/2\gamma]\Delta p/p_0 < 1\}$ being the measure of the maximum pressure disturbances Δp relative to the atmospheric pressure p_0 and γ the ratio of the specific heats for the air. A characteristic frequency of the pressure disturbances is designated by ω , while ω_0 denotes the natural frequency of the resonator given by $(B\alpha_0^2/LV)^{1/2}$ where B and L denote, respectively, the passage's cross-sectional area and its length, α_0 being the sound speed.

The parameter κ determines the size of the cavity's volume V relative to the tunnel's volume per spacing Ad , while the latter Ω determines the size of the passage's cross-sectional area B and its length L . It is shown that the array of the resonators is very effective if κ is chosen large enough to be 10, while Ω is set greater than unity. For the double array, two 'coupling parameters' $\kappa_i (i=1,2)$ and 'tuning parameters' $\Omega_i (i=1,2)$ control the effect of the array:

$$\kappa_i = \frac{V_i}{2\epsilon A d_i} \quad \text{and} \quad \Omega_i = \left(\frac{\omega_{0i}}{\omega}\right)^2,$$

where the suffix i designates the respective quantities pertinent to the array 1 and 2. It is found that the choice of the coupling parameters even smaller than 10 is enough if Ω_1 is set equal to unity, while Ω_2 is set far greater than unity, for example $\Omega_1 = 1$ and $\Omega_2 = 5$ for $\kappa_1 = \kappa_2 = 1$.

BRIEF DESCRIPTION OF THE DRAWINGS

- Figure 1. A tunnel to which a cavity is connected in array through a passages.
- Figure 2. A tunnel with a side tunnel partitioned into compartments as a cavity by the bulkhead.
- Figure 3. Two tunnels sharing one side tunnel with the connecting passages having suitable dampers or bulkheads.
- Figure 4. A tunnel to which the two different kind of cavities and passages are connected.
- Figure 5. A tunnel with a side tunnel partitioned into two different sizes of compartments and connected by two different sizes of passages.
- Figure 6. Geometrical configuration of the problem.
- Figure 7. Dispersion relation where (a) shows the absolute value of the imaginary part of S , S_i , versus ω_0/ω while (b) shows its real part S_r versus ω_0/ω .
- Figure 8. Evolution of pressure disturbances in the tunnel without the array of resonators where the normalised pressure f in the tunnel is shown and the vertical arrow measures unity of f .
- Figure 9. Evolution of pressure disturbances in the tunnel with the array of resonators having $\kappa = 1$ and $\Omega = 1$ where (a) and (b) show the normalised pressure f and g in the tunnel and in the cavity, respectively and the vertical arrow measures unity of the respective quantity.
- Figure 10. Evolution of pressure disturbances in the tunnel with the array of resonators having $\kappa = 10$ and $\Omega = 1$ where (a) and (b) show the normalised pressure f and g in the tunnel and in the cavity, respectively and the vertical arrow measures unity of the respective quantity.
- Figure 11. Evolution of pressure disturbances in the tunnel with the array of resonators having $\kappa = 1$ and $\Omega = 10$ where (a) and (b) show the normalised pressure f and g in the tunnel and in the cavity, respectively and the vertical arrow measures unity of the respective quantity.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FORMULATION OF THE PROBLEM

In considering the sound field generated by travelling of a train, it is important to distinguish between a near field and a far field from the train. In the near field, many sources of sound are identified, especially, to be attributed to a train's geometry as well as a tunnel's one. In this field, very complicated sound field of three-dimensional nature is built up, involving a wide range of frequencies. With the distance away from the train, however, high-frequency components in the complicated behaviour will fade out due to the significant dissipation so that almost one-dimensional propagation will survive along the tunnel in the far field.

To determine its typical frequency, no other physical quantities are available than the tunnel's diameter D , the train's speed U and its axial length l . These quantities suggest the frequency to be determined by α_0/l or U/D . Suppose, for example, that the train of length 200 m be travelling with a speed 150 m/s (540 km/h) in a tunnel of diameter 10m. The former estimation gives the frequency of a few Hertz, while the latter also gives a similar frequency, even if the Doppler effect is taken into account. In the far field, thus, the infra-sound will be propagated.

As for their magnitude, the maximum magnitude of the pressure disturbances could be generated when the trains suddenly sets into motion with a constant speed U . The linear acoustic theory predicts that its magnitude is given roughly by $\beta M/(1-M)$ relative to the atmospheric pressure where β denotes the ratio of the train's cross-sectional area to the tunnel's one and $M (= U/\alpha_0 < 1)$ denotes the train's Mach number. This suggests the higher pressure disturbances as the train's speed M approaches unity. Since the infra-sound is subjected to less dissipation in propagation, it is highly probable that the nonlinearity accumulates to give rise eventually to emergence of shock waves in the far field.

In view of the physical consideration above, we formulate the propagation of pressure disturbances in the tunnel with the array of resonators shown in Fig.1. For simplicity, let identical resonators be connected with the axially equal spacing and take this spacing much smaller than the characteristic wavelength so that the resonators may be regarded as continuously distributed along the tunnel. In formulation, the effect of friction at the tunnel wall is taken into account whereas the effect of diffusivity of sound itself is ignored. The wall friction is important in evaluating the far-field behaviour quantitatively because it exhibits such a hereditary effect as to accumulate in the course of propagation.

By taking account of this wall friction, at first, we derive the nonlinear wave equations for the far-field propagation of pressure disturbances in the tunnel with the array of resonators. Examining the linear dispersion relation, we look at the effect of the array of resonators on propagation of infinitesimally small pressure disturbances. By solving typical initial-value problems for the equations, next, we describe the effect of resonators in propagation of pressure disturbances and especially in suppression of emergence of shock waves.

For a far-field behaviour, the quasi-one-dimensional propagation is assumed for the acoustic main flow in the tunnel except for a thin boundary layer adjacent to the tunnel wall and a vicinity of the orifices from the resonators (see Fig.6). Here the term 'quasi-one dimension' is used in the sense that the cross-section of the acoustic main flow varies slowly along the tunnel. For this main flow, the equation of continuity is given by

$$(1) \quad \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = \frac{1}{A} \int \rho v_n ds ,$$

where ρ and u denote, respectively, the mean values of the density and the axial velocity of the air averaged over the cross-section of the main flow, x and t being the axial coordinate and the time. The right-hand side represents the mass flux density ρv_n into the main flow through the edge of the boundary layer and the orifices of the resonators, v_n being the small velocity inward normal to the boundary of the cross-section of the main flow and ds the line element along it.

The diffusivity of sound is neglected so the equation motion for the main flow in the axial direction is given by

$$(2) \quad \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = - \frac{1}{\rho} \frac{\partial p}{\partial x} ,$$

where p is the mean pressure averaged over the cross-section of the main flow. In addition to these two equations, there exists between p and ρ the adiabatic relation $p/p_0 = (\rho/\rho_0)^\gamma$ where the suffix 0 implies the respective equilibrium values. For closure of the equations, it is necessary to specify the mass flux on the right-hand side of (1) due to the boundary layer and the resonators. The boundary layer consists of two layers for the velocity and the temperature. It is known that the velocity at the edge of the boundary layer v_b corresponding to v_n is given in terms of the velocity in the main flow by

$$(3) \quad v_b = C \left(\frac{\nu}{\pi}\right)^{1/2} \int_{-\infty}^t \frac{1}{\sqrt{t-t'}} \frac{\partial u(x, t')}{\partial x} dt' ,$$

with $C = 1 + (\gamma-1)/Pr^{1/2}$ where ν is the kinematic viscosity and Pr is the Prandtl number. The velocity v_b is given by the hereditary integral of u with respect to the past time t' up to t . This integral is nothing but the x derivative of the fractional derivative of order minus 1/2 for u defined by

$$(4) \quad \frac{\partial^{-1/2} u}{\partial t^{-1/2}} = \frac{1}{\pi} \int_{-\infty}^t \frac{1}{\sqrt{t-t'}} u(x, t') dt' .$$

To derive another contribution to the mass flux from the resonator, it is necessary to examine its response. Let the resonator consist of the cavity of volume V and the passage as a throat of cross-sectional area B and of length L and let all length-scale be much shorter than a characteristic wavelength of pressure disturbances. Assuming the cavity's volume be far larger than that of throat, the motion in the cavity is neglected so that only the conservation of mass is considered:

$$(5) \quad V \frac{\partial \rho_c}{\partial t} = B q ,$$

where ρ_c is the averaged density of air in the cavity and q denotes the mass flux through the throat from the tunnel to the cavity. The compressibility of the air in the throat can be ignored because the throat's length is much shorter than the characteristic wavelength. Hence the mass flux from the throat into the tunnel ρv_n is constant along the throat and is equal to $-q$. For the air in the throat, the equation of motion in the axial direction can be averaged over the whole cross-section of the throat including the boundary layer as

$$(6) \quad \frac{\partial}{\partial t} (\overline{\rho v}) + \frac{\partial}{\partial y} (\overline{\rho v^2}) = - \frac{\partial p}{\partial y} - \frac{\sigma}{B} ,$$

where y denotes the axial coordinate along the throat with its origin at the orifice to the tunnel. Here ρ , v , p denote, respectively, the density of the air in the throat, its velocity in the y direction and the pressure where the bar designates the averaged quantity over the cross-section. The wall friction σ per unit axial length can be evaluated by examining the boundary layer near the throat wall. But since the air in the throat can be regarded as being incompressible, we have only to consider the boundary layer for the velocity unlike in the case for the tunnel. In this consequence, σ can be given by the following hereditary integral:

$$(7) \quad \sigma = \frac{2B}{r} \left(\frac{\nu}{\pi}\right)^{1/2} \int_{-\infty}^t \frac{1}{\sqrt{t-t'}} \frac{\partial q(x, t')}{\partial t'} dt' ,$$

whether r is the hydraulic radius of the throat. Because this integral corresponds to the first-order derivative of the fractional derivative of minus $1/2$ for q with respect to t , it is called the derivative of order $1/2$.

For the motion in the throat, we linearise to neglect the quadratic momentum flux density (where ρ is close to ρ_0) and integrate (6) from one orifice at the tunnel side $y=0$ to the other one at the cavity side $y=L$. Here note again that ρv averaged over the cross-section is equal to q and that q and σ are independent of y . It is assumed that the pressure at $y=0$ is equal to that in the tunnel at that section, while the pressure at $y=L$ is equal to that in the cavity p_c . In order to express q in (5) in terms of p_c , the adiabatic relation is linearised as $dp_c/d\rho_c = \alpha_0^2$. Then we derive the 'differential equation' for $p'_c (= p_c - p_0)$ with $p' (= p - p_0)$:

$$(8) \quad \frac{\partial^2 p'_c}{\partial t^2} + \frac{2\nu^{1/2}}{r} \frac{\partial^{3/2} p'_c}{\partial t^{3/2}} + \omega_0^2 p'_c = \omega_0^2 p'_0 ,$$

where $\omega_0^2 (= B\alpha_0^2/LV)$ is the natural frequency of the resonator and the derivative of order $3/2$ is defined as the one by differentiating the derivative of order $1/2$ once with respect to t .

We now complete the mass flux on the right-hand side of (1). For the resonators almost continuously distributed with the axially equal spacing d , let their number density be $N (= 1/d)$. Then the mass flux per unit axial length can be given as

$$(9) \quad \frac{1}{A} \int \rho v_n ds \cong \frac{1}{A} \left[\left(\frac{2A}{R} - NB \right) \rho_0 v_b - NBq \right] ,$$

where R is the hydraulic radius of the tunnel and NB accounts for the total cross-sectional area of the orifices per unit axial length. Thus (1), (2) and (8) are closed for ρ , u and p'_c . But using the local sound speed $\alpha = (dp/d\rho)^{1/2} = \alpha_0 (\rho/\rho_0)^{(\gamma-1)/2}$ instead of ρ , (1) and (2) are finally reduced to the following equations:

$$(10) \quad \left[\frac{\partial}{\partial t} + (u \pm a) \frac{\partial}{\partial x} \right] (u \pm \frac{2}{\gamma-1} a) \\ = \pm \frac{2Ca_0 \nu^{1/2}}{R^*} \frac{\partial^{-1/2}}{\partial t^{-1/2}} \left(\frac{\partial u}{\partial x} \right) + \frac{NV}{A\rho_0 a_0} \frac{\partial p'_c}{\partial t} ,$$

with the sign vertically ordered where $1/R^*$ is defined as $[1-NRB/2A]/R$ with $B/A = (r/R)^2$. The left-hand sides of the equations describe the well-known unsteady one-dimensional flow of compressible gas, while the right-hand sides describe the effects of the wall friction and the resonators. To pick up the propagation along the positive direction of the x axis, we introduce the nondimensional retarded time $\theta [= \omega(t-X/\alpha_0)]$, ω : the characteristic frequency of pressure disturbances] and the far-field variable $X (= \epsilon \omega X / \alpha_0)$ associated with the order of nonlinearity ϵ ($\ll 1$). In addition to θ and X , we set $[(\gamma+1)/2]u/\alpha_0$ and $[(\gamma+1)/2\gamma] p'_c/p_0$ to be ϵf and ϵg , respectively and neglect higher order terms in ϵ . Then (10) and (8) are reduced to the following equations:

$$(11) \quad \frac{\partial f}{\partial X} - f \frac{\partial f}{\partial \theta} = -\delta_R \frac{\partial^{1/2} f}{\partial \theta^{1/2}} - \kappa \frac{\partial g}{\partial \theta} ,$$

$$(12) \quad \frac{\partial^2 g}{\partial \theta^2} + \delta_r \frac{\partial^{3/2} g}{\partial \theta^{3/2}} + \Omega g = \Omega f ,$$

where

$$(13) \quad \delta_R = \frac{C (\nu/\omega)^{1/2}}{\epsilon R^*}, \quad \kappa = \frac{V}{2\epsilon A d},$$

$$\delta_r = \frac{2 (\nu/\omega)^{1/2}}{r} \quad \text{and} \quad \Omega = \left(\frac{\omega_0}{\omega}\right)^2$$

are the constants. Here δ_R and δ_r designate the ratio of the boundary-layer thickness $(\nu/\omega)^{1/2}$ to the radius of the tunnel and that of the throat, respectively, while κ and Ω are the coupling parameter and the tuning parameter, respectively, through which the effect of the array of resonators is taken into account.

Let us now evaluate numerically these coefficients. As a typical example, a tunnel of diameter 10m is assumed with the resonator having a spherical cavity of diameter of 4m and a throat of diameter 1m and of length 3m. Then the natural frequency ω_0 is given by 4.8 Hz for $\alpha_0 = 340\text{m/s}$. For a characteristic frequency $\omega = 5$ Hz, we have $\delta_R = 2.0 \times 10^{-4}/\epsilon$, $\delta_r = 2.7 \times 10^{-3}$ and $\kappa = 2.1 \times 10^{-2}/\epsilon$ for $d = 10\text{m}$ ($N = 0.1/\text{m}$) where $\gamma = 1.4$, $Pr = 0.72$ and $\nu = 1.45 \times 10^{-5} \text{m}^2/\text{s}$. If the pressure level ϵ is assumed to be 0.002, δ_R and κ take the values 0.1 and 10, respectively.

LINEAR DISPERSION RELATION

Before proceeding to the nonlinear problem, we examine the effect of the array of resonators on propagation of pressure disturbances of infinitesimally small amplitude. Assuming f and g be in the form of $\exp[i(\theta - SX)]$ (S : constant) and linearising (11), S becomes complex. Its imaginary part S_i

$$(14) \quad S_i = -\frac{1}{\sqrt{2}} \left[\delta_R + \frac{\kappa \delta_r \Omega}{(\Omega - 1 - \delta_r \sqrt{2})^2 + \delta_r^2/2} \right]$$

gives the spatial damping rate with respect to X . The first term in the square bracket gives the inherent decay due to the wall friction while the second term gives the enhancement in the decay by the array of the resonators. Figure 7(a) shows the absolute value of S_i versus $\omega_0/\omega (= \Omega^{1/2})$. It has the maximum damping rate $|S_i| \cong 2^{1/2} \kappa / \delta_r$ at $\omega_0/\omega = 1 + \delta_r/2^{1/2} + \dots$. Thus if ω_0 is chosen close to ω , the decay can be enhanced.

On the other hand, the real part of S , S_r , corresponds to the inverse of propagation velocity. It is given by

$$(15) \quad S_r = \frac{1}{\sqrt{2}} \delta_R + \frac{\kappa \Omega (\Omega - 1 - \delta_r \sqrt{2})}{(\Omega - 1 - \delta_r \sqrt{2})^2 + \delta_r^2/2}.$$

Figure 7(b) shows S_r versus $\omega_0/\omega (= \Omega^{1/2})$. In the limit as $\omega_0/\omega \rightarrow 0$, S_r approaches $\delta_r/2^{1/2}$ for the value without the array, while in the other limit as $\omega_0/\omega \rightarrow \infty$, S_r approaches $\delta_r/2^{1/2} + \kappa$. Between these limits, the array of resonators gives rise to the dispersion. Here note that the wall friction itself also contributes to the dispersion but it is small and secondary compared with the one due to the array of resonators.

EFFECT OF THE ARRAY OF RESONATORS ON EVOLUTION OF PRESSURE DISTURBANCES

By solving an initial (physically boundary) value problem for (11) and (12), we examine the effect of the array of resonators. To this end, it is convenient to express them in the 'characteristic form'. Along the 'characteristics' defined by

$$(16) \quad \frac{d\theta}{dX} = -f,$$

(11) and (12) can be written as

$$(17) \quad \frac{df}{dX} = -\delta_R \frac{\partial^{1/2} f}{\partial \theta^{1/2}} - \kappa \frac{\partial g}{\partial \theta},$$

$$(18) \quad \frac{\partial^2 g}{\partial \theta^2} + \delta_r \frac{\partial^{3/2} g}{\partial \theta^{3/2}} + \Omega g = \Omega f,$$

As a typical initial condition for f at $X=0$, we consider a pair of positive (compression) and negative (expansion) pulses given by the derivative of the Gaussian-shaped pulse:

$$(19) \quad f(\theta, X=0) = -\sqrt{2e} \theta \exp(-\theta^2),$$

where the factor $(2e)^{1/2}$ is introduced to normalize the maximum of f . The initial value for g is determined as the solution to (18) with f prescribed by (19). If the wall friction and the array of resonators are ignored, the initial profile given by (19) evolves into two shock waves known as the so-called N-wave. So we compare with the evolution from (19) in the tunnel without the array and that in the tunnel with the array. In the following, δ_R and δ_r are fixed to be 0.1 and 0.01, respectively.

At first, Fig.8 shows the evolution in the tunnel without the array of resonators. This case corresponds formally to setting $\kappa=0$ in (17). Here f corresponds to the pressure p' in the tunnel relative to the atmospheric pressure through $\epsilon f = [(\gamma+1)/2\gamma] p'/p_0$. It is seen that two shock waves (i.e., discontinuity in profile) emerge at $X=1.0265$ and $X=1.0530$, respectively. It is also seen that the discontinuity appears rounded on its right-hand side and the long tail appears by the hereditary effect due to the wall friction. For $\omega = 5$ Hz and $\epsilon = 0.002$, in passing, the unity in X corresponds to about 5 km.

We now demonstrate the evolution in the tunnel with the array of resonators. The coupling parameter κ is chosen to be unity while the tuning parameter Ω is also chosen to be unity so that the large decay can be expected. Figure 9(a) shows the evolution of f from $X=0$ to $X=2$. The leading shock wave appears at $X=0.8630$, while the trailing one appears at $X=1.2960$. Comparing this figure with the one without the array, the trailing shock wave appears earlier and it grows faster and becomes positive. Figure 9(b) shows the evolution of g where the direction of X is reversely taken so that the oscillatory initial profile of g can be seen. It is found that this size of the resonator is useless for suppression of emergence of shock waves.

Next we show the evolution for a larger value of the coupling parameter $\kappa=10$. It is evident from (14) that the damping rate is increased with κ . Figure 10(a) shows that the initial profile evolves into ripples with no indication of emergence of shock waves. Figure 10(b) shows the evolution of g , which quickly decays out. Thus it is found that the size of the resonator can suppress propagation of pressure disturbances and emergence of shock waves in the far field.

For $\Omega \ll 1$ or $\Omega \gg 1$, the linear damping rate is small. For $\Omega=0.1$, it is found that two shock waves emerge even for $\kappa=10$. But for $\Omega=10$, interestingly enough, the initial pressure disturbances evolve smoothly without any shock waves even for $\kappa=1$ as shown in Fig.11, although their magnitude does not decay out so pronouncedly as in the case shown in Fig.10 because of the small damping rate. No emergence of shock waves in this case results from the dispersion of acoustic waves caused by the array of resonators. To see this, in fact, g in (12) is approximated for $\Omega \gg 1$ by

$$(20) \quad g = f - \frac{1}{\Omega} \left(\frac{\partial^2 g}{\partial \theta^2} + \delta_r \frac{\partial^{3/2} g}{\partial \theta^{3/2}} \right)$$

$$= f - \frac{1}{\Omega} \left(\frac{\partial^2 f}{\partial \theta^2} + \delta_r \frac{\partial^{3/2} f}{\partial \theta^{3/2}} \right) + O\left(\frac{1}{\Omega^2}\right).$$

Substituting this into (11) and neglecting the small terms with δ_R , we have the well-known Korteweg-de Vries equation. This equation suggests that the array gives rise to the higher-order dispersion, which can now compete with the nonlinear steepening to suppress emergence of shock waves. In this case, it is expected that 'acoustic soliton' may emerge in a 'far' far field. This acoustic soliton is propagated in the form of a pulse rather than a shock wave and its width is determined by x/Ω . Thus if Ω is taken extremely large so that x/Ω becomes small, there may appear another noise problem associated with propagation of this pulse.

Upon examining evolutions in various cases of the parameters x and Ω , generally speaking, it is found that for $\Omega \approx 1$, propagation of pressure disturbances is significantly suppressed so that emergence of shock waves can be avoided if x is taken as great as 10. It is also found that for a fixed value of x such as unity, emergence of shock waves can be avoided as Ω is taken greater than unity. But the propagation of pressure disturbances persists over a long distance without shock waves. These results still hold for even smaller value of δ_r such as 0.0027.

For other types of initial condition, the evolution is examined for a single Gaussian-shaped pulse given by

$$(21) \quad f(\theta, X=0) = \exp(-\theta^2).$$

Then it is confirmed that the results derived for the condition (19) hold similarly.

NONLINEAR EFFECT OF RESONATORS

Next we examine the case with the high pressure level of ϵ such as $\epsilon = 0.1$ (corresponding to 175 dB in SPL). As the pressure level is increased, the nonlinear response of the resonator is enhanced, especially, due to the nonlinear loss due to the jet flow formed on leaving the orifice of the resonators. Then (12) is modified to include the nonlinear response of the resonator $\epsilon\psi$:

$$(22) \quad \frac{\partial^2 g}{\partial \theta^2} + \delta_r \frac{\partial^{3/2} g}{\partial \theta^{3/2}} + \Omega g = \Omega f + \epsilon \psi,$$

where $\epsilon\psi$ is defined as

$$(23) \quad \epsilon \psi = \epsilon \left[\left(\frac{\gamma-1}{\gamma+1} \right) \frac{\partial^2 g^2}{\partial \theta^2} - \frac{2}{\gamma+1} \frac{(a_0/\omega L_e)^2}{\Omega^2} \left| \frac{\partial g}{\partial \theta} \right| \frac{\partial g}{\partial \theta} \right],$$

where L_e stands for the effective length of the throat with the end corrections. The first term represents the nonlinearity resulting from the adiabatic change in the cavity, and the second terms represents the nonlinear loss due to the jet flow. On deriving the resonator's response, the length of the throat is assumed to be much shorter than the characteristic wavelength, i.e., $a_0/\omega L_e \gg 1$. But this loss may be neglected by taking ϵ to be sufficiently small. As ϵ becomes large, however, it becomes prominent, particularly, for a small value of Ω , whereas the effect of wall friction becomes small in comparison with the nonlinearity (see the definition of δ_R).

Here we remark the end corrections. When the effective length of the throat is introduced, L in the definition of ω_0 should be replaced by L_e accordingly. In addition, the end corrections for the wall friction may also be made by lengthening L to L' so that the definition of δ_r is multiplied by a factor L'/L_e . In our

formulation, we take the position that these quantities are to be determined experimentally. To simplify the discussion, however, we ignore the end corrections to set $L_e = L' = L$, bearing in mind that they might modify results quantitatively.

As a case with higher pressure level, we consider another tunnel of smaller diameter 7m with the resonator having a spherical cavity of diameter 6m and the throat of diameter 2m and of length 3m. For this tunnel, the natural frequency ω_0 is given by 5.2 Hz and $\delta_R = 2.8 \times 10^{-4}/\epsilon$, $\delta_r = 1.4 \times 10^{-3}$ and $x = 1.5 \times 10^{-1}/\epsilon$ for the same spacing $d = 10$ m. Here if ϵ is assumed to be 0.1, x , i.e., the effective size of the resonator is much smaller than 10 but $\epsilon(\alpha_0/\omega L)^2$ now takes a large value 1.3. It should be remarked here that the ratio V/Ad ($= 2\epsilon x$) cannot be taken large because it controls the degree of reflection at each resonator and the derivation of the governing equations is based on the assumption of small reflection by each resonator, i.e., $V/Ad \ll 1$.

The effect of the array of resonators is examined. It is found that for $x = \Omega = 1$, there emerge shock waves from both initial conditions (19) and (21) even if the nonlinear loss is taken into account. But as Ω is increased to 10, there is no indication of shock waves at all. It is confirmed that the results obtained for the lower pressure disturbances still hold for this case.

EFFECT OF DOUBLE ARRAY

In addition to the single array of resonators, we examine the effect of the double array. For this array, two 'coupling parameters' κ_i ($i = 1, 2$) and 'tuning parameters' Ω_i ($i = 1, 2$) control the effect of the array:

$$\kappa_i = \frac{V_i}{2\epsilon A d_i} \quad \text{and} \quad \Omega_i = \left(\frac{\omega_{0i}}{\omega} \right)^2,$$

where the suffix i designates the respective quantities pertinent to the array 1 and 2. The far-field propagation of pressure disturbances is described by the following equations:

$$(24) \quad \frac{\partial f}{\partial X} - f \frac{\partial f}{\partial \theta} = -\delta_R \frac{\partial^{1/2} f}{\partial \theta^{1/2}} - \kappa_1 \frac{\partial g_1}{\partial \theta} - \kappa_2 \frac{\partial g_2}{\partial \theta},$$

$$(25) \quad \frac{\partial^2 g_1}{\partial \theta^2} + \delta_{r1} \frac{\partial^{3/2} g_1}{\partial \theta^{3/2}} + \Omega_1 g_1 = \Omega_1 f,$$

$$(26) \quad \frac{\partial^2 g_2}{\partial \theta^2} + \delta_{r2} \frac{\partial^{3/2} g_2}{\partial \theta^{3/2}} + \Omega_2 g_2 = \Omega_2 f,$$

where f , g_1 and g_2 correspond to the pressure appropriately normalized in the tunnel, in the cavity of the array 1 and 2, respectively and δ_{ri} ($i = 1, 2$) are defined by the hydraulic radius of each throat. By solving evolution problems for (24)-(26), it is found that the choice of the coupling parameters even smaller than 10 is enough if Ω_1 is set equal to unity while Ω_2 is set far greater than unity, for example $\Omega_1 = 1$ and $\Omega_2 = 5$ for $\kappa_1 = \kappa_2 = 1$. For this choice, the initial pressure disturbances are decayed out very quickly.

EFFECT OF INVENTION

By the numerical simulation of the spatial evolutions of the pressure disturbances in the tunnel with the structure proposed, it is proved that the array of resonators is very effective in suppressing propagation of pressure disturbances and especially emergence of shock waves. In order for the array to be effective, of course, a greater value of x should be chosen for $\Omega = 1$ as far as the basic assumption of the small reflection ($V/Ad \ll 1$) is not violated. Furthermore if the double (multiple) array can be connected, its effect is enhanced significantly.

In addition, it is the important finding that if Ω is set to a greater value than unity, e.g., 10, even smaller value of x such as unity is enough for suppression of emergence of shock waves but the propagation of

pressure disturbances persists over a long distance. This is due to the higher-order dispersion introduced by the array of resonators.

For Ω much smaller than unity, e.g., 0.1, there always appear shock waves even for a large value of x . This results from the fact that for $\Omega \ll 1$, the array introduces only the lower-order dispersion which cannot counteract the nonlinearity to allow emergence of shock waves. It is concluded finally that after the shock waves are once formed, the array of resonators is inactive for them and therefore, before that, dispersing the pressure disturbances is essential for suppression of emergence of shock waves.

Claims

1. A tunnel-structure where many cavities are arranged in the outside of the tunnel and in array axially and each cavity is connected to the tunnel through a connecting passage(s) so that propagation of pressure disturbances can be suppressed and especially emergence of acoustic shock waves can be avoided.

FIG. 1

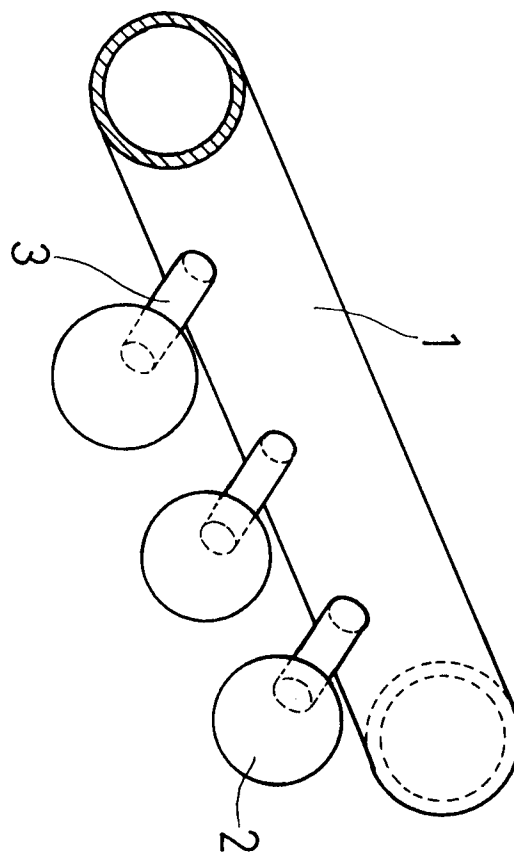


FIG. 2

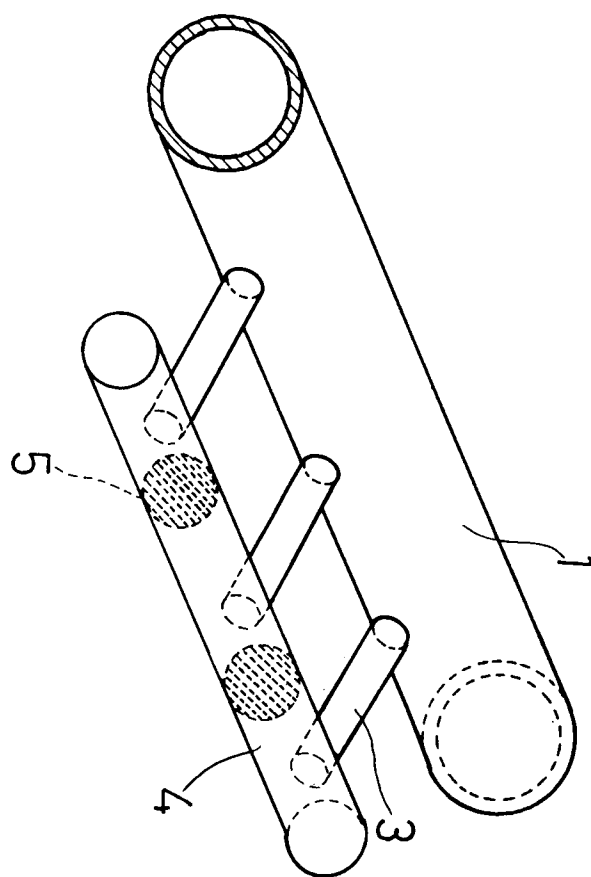


FIG.3

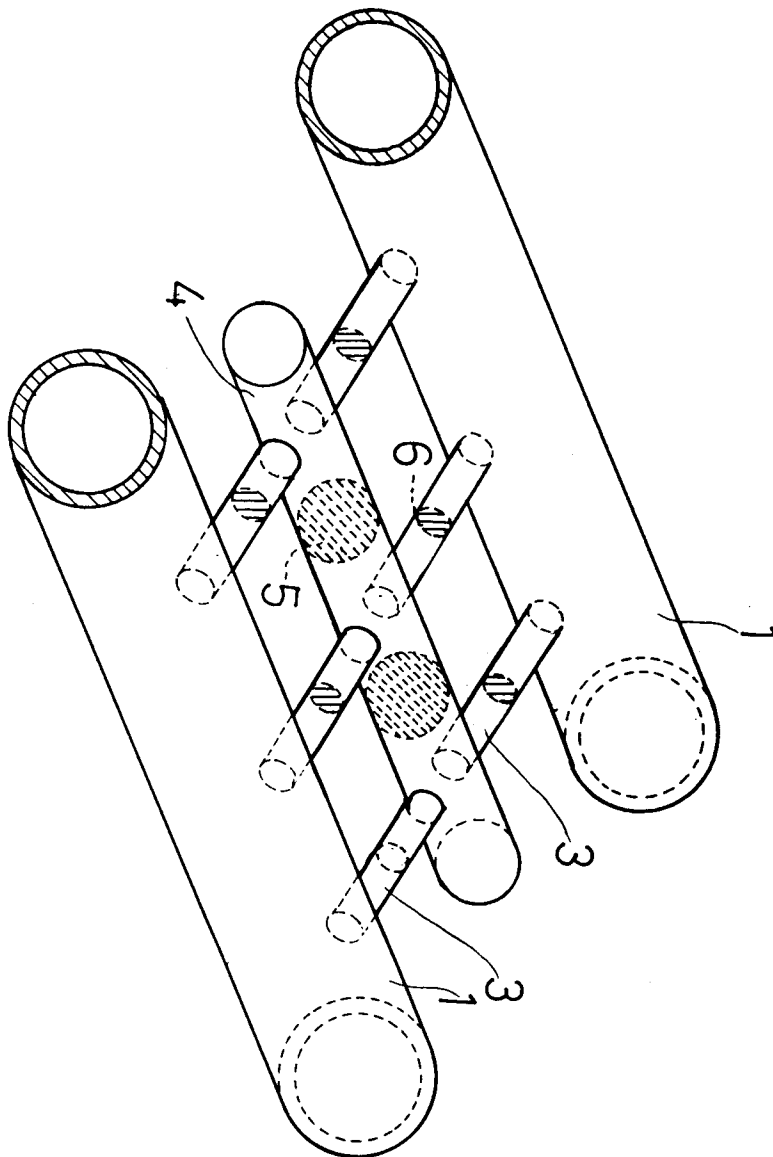


FIG.4

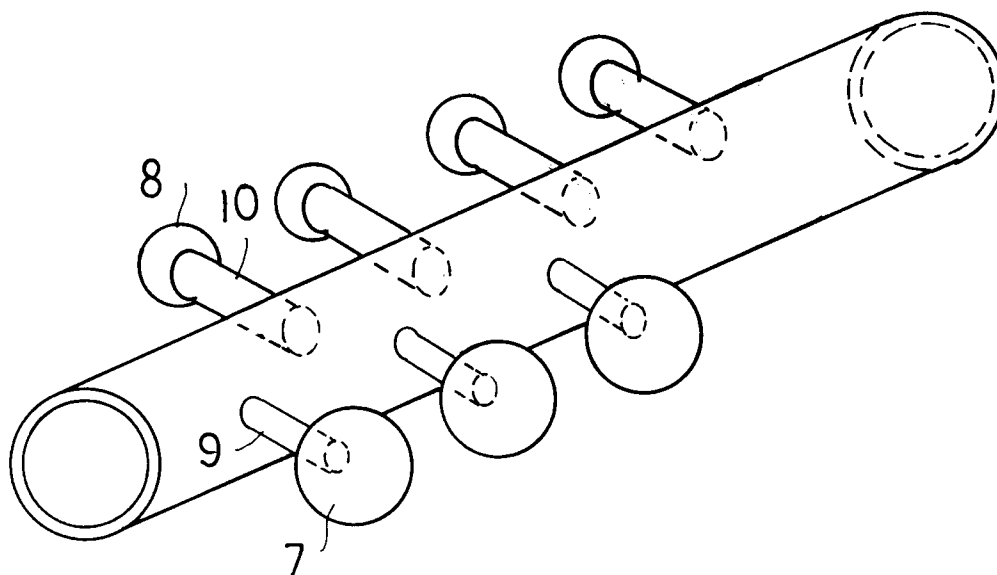


FIG.5

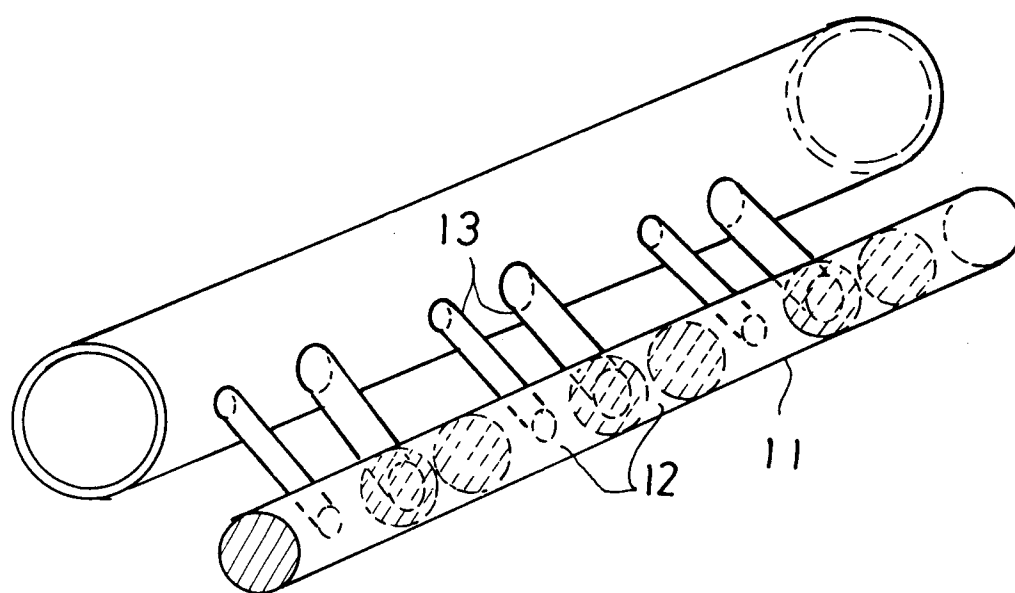


FIG.6

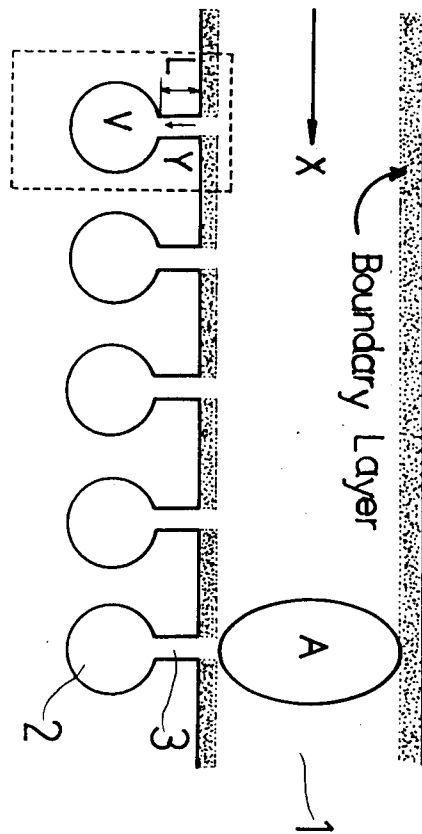


FIG.7

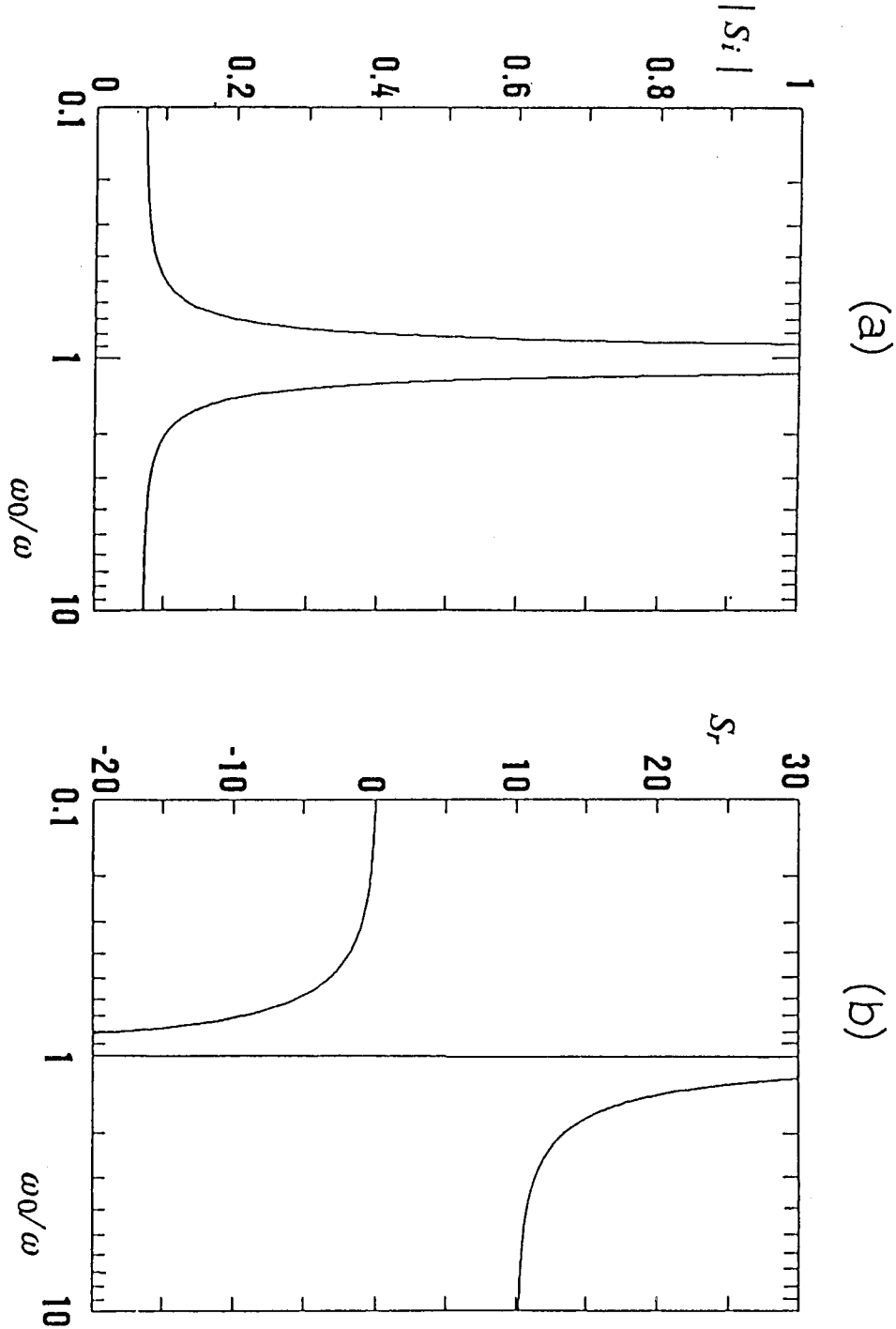


FIG.8

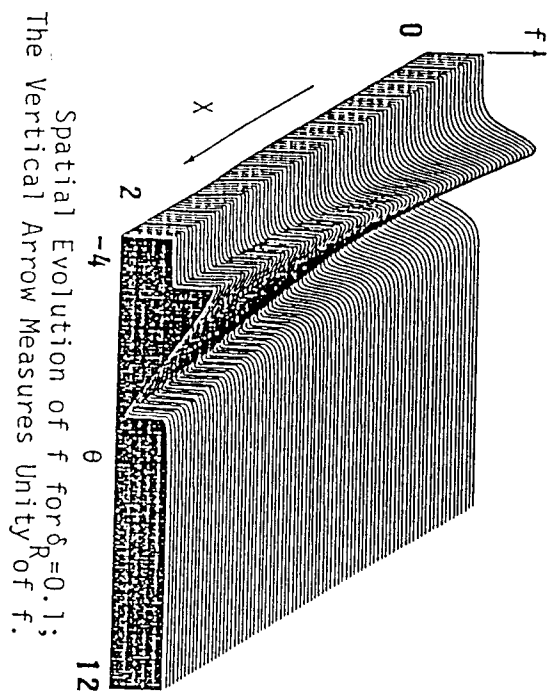
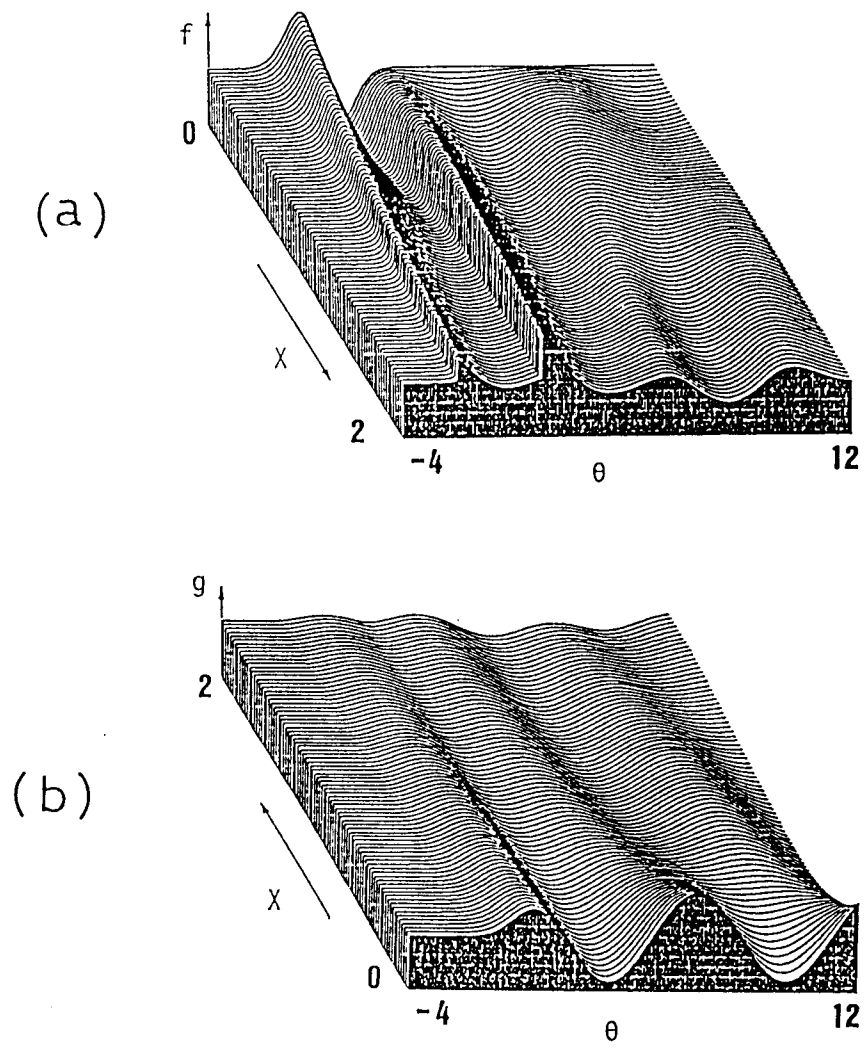
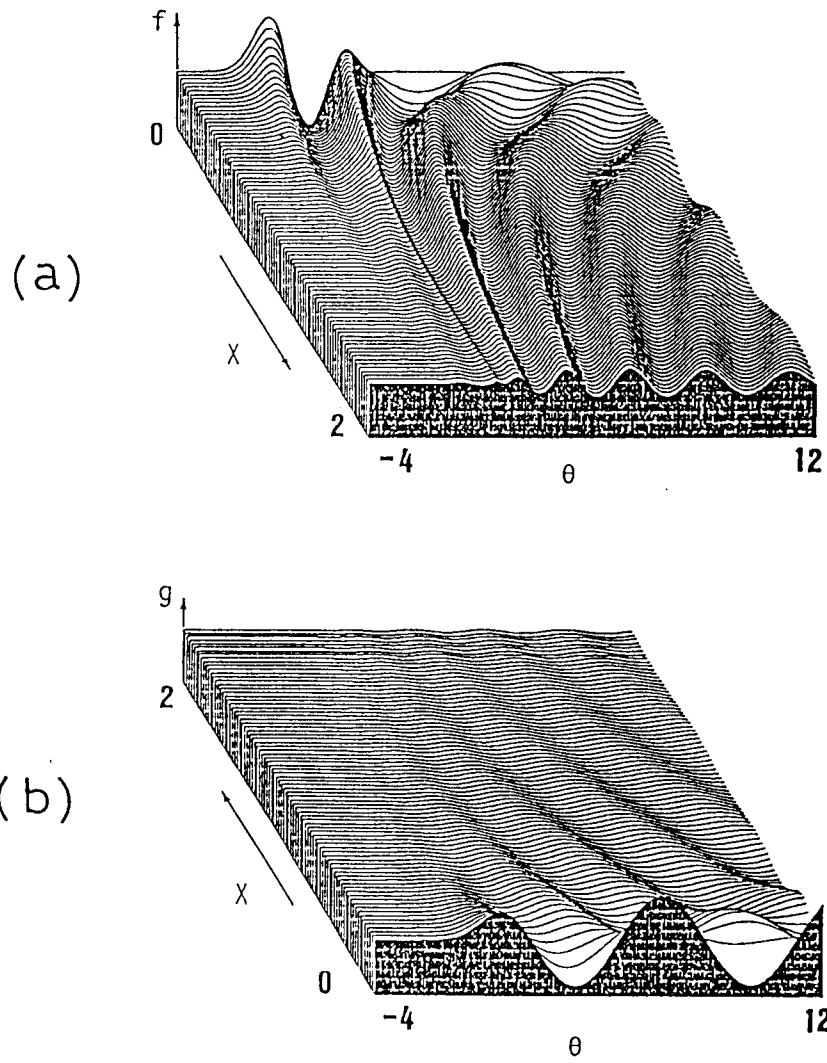


FIG.9



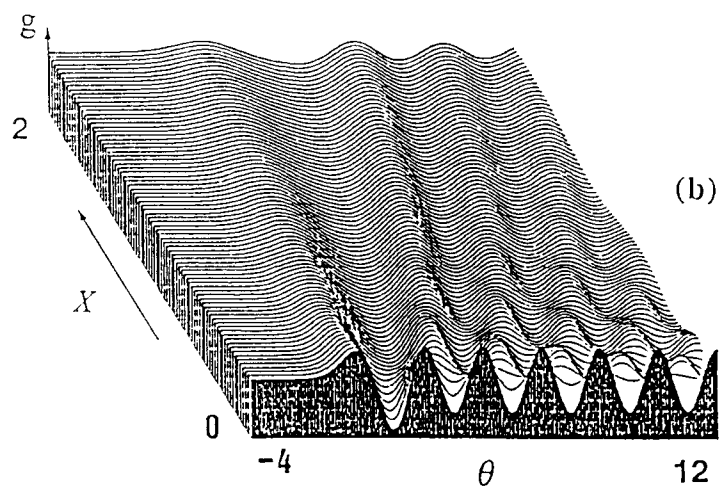
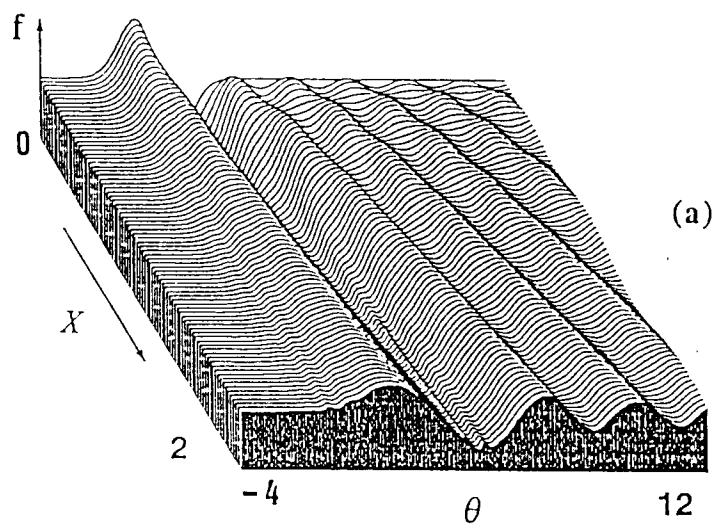
Spatial Evolution of f and g for $\kappa=1$, $\Omega=1$, $\delta_R=0.1$ and $\delta_r=0.01$; The Vertical Arrows Measure Unity of r and g .

FIG.10



Spatial Evolution of f and g for $\kappa=10$, $\Omega=1$, $\delta_i=0.1$ and $\delta_r=0.01$; The Vertical Arrows Measure Unity of f and g .

FIG.11



U 330 T : $\delta_R = 0.1$, $\delta_\Gamma = 0.01$, $\overset{\ell=0}{W} = 10$, $K = 1$;
 $-4 < \theta < 12$, $0 < X < 2$, (-3.6)