EFFECTIVENESS OF ATTENUATING SHOCK WAVES IN CHANNELS BY VARIOUS METHODS

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A channel with an expanding cross section [1-7], perforation of the lateral walls [2, 8-13], permeable barrier screens mounted either singly or in a cascade [14-31], packed beds [32-34], porous barriers [35-37], suspended solids [38-45], etc., are used to attenuate shock waves. Here we compare the effectiveness of attenuating air shock waves by various methods. In order to analyze the shock wave attenuation, we use a single approach [1, 4] which gives satisfactory agreement with experimental observations.

1. Attenuating Shock Waves in an Expanding Channel. A simple method [1, 4] has been suggested for calculating the propagation of a plane step shock wave in a channel with a variable cross section. The essence of the method is the assumption that the wave front satisfies the relationship for the C_+ characteristic. Actually, it is assumed that the propagation velocity for acoustic perturbations in the region behind the shock wave is equal to the velocity of the front. The accuracy of the assumption is discussed in [4] and [30]. It is shown that for $1 < M < \infty$ the relative velocity difference is bounded and does not exceed 30%, which is completely acceptable for many applications. Comparison of the approximate solution with numerical calculation shows that this assumption gives good accuracy [4, 30, 17].

In the case of a shock wave propagating in an expanding channel, the quasi-one-dimensional equation for the C_+ characteristic has the form

$$\frac{u+a}{\rho u a^2}\frac{dp}{dx}+\frac{u+a}{ua}\frac{du}{dx}=-\frac{1}{A}\frac{dA}{dx}, \tag{1.1}$$

where u is the gas velocity, a is the sound speed, ρ is the density, p is the pressure, A is the area of the cross section, and x is the shock-wave propagation distance. Substitution of jump conditions into (1.1) gives the dependence of the Mach number M for the shock wave on x:

$$\frac{M}{M^2-1}\lambda(M)\,dM/dx=-A^{-1}dA/dx. \tag{1.2}$$

Here

$$\lambda(M)=[1+2(1-\mu^2)/\mu(\gamma+1)](1+2\mu+M^{-2});$$
$$\mu^2=[(\gamma-1)M^2+2][2\gamma M^2-(\gamma-1)];$$

and γ is the ratio of the gas heat capacities. By assuming dA/dx = const, $M(0) = M_0$, and $A(0) = A_0$, we obtain the solution to (1.2):

$$G_e(M)/G_e(M_0)-1=X_e, \tag{1.3}$$

where $X_e \equiv A_0^{-1}(dA/dx)\cdot x$ is the dimensionless shock wave propagation distance. Here and hereafter it is assumed that in the section x < 0 the shock wave propagates with a constant velocity $M = M_0$. The function $G_e(M)$ is given by the relationship

$$G_e(M)=\exp\left\{-\int\frac{M\lambda(M)}{M^2-1}dM\right\}$$

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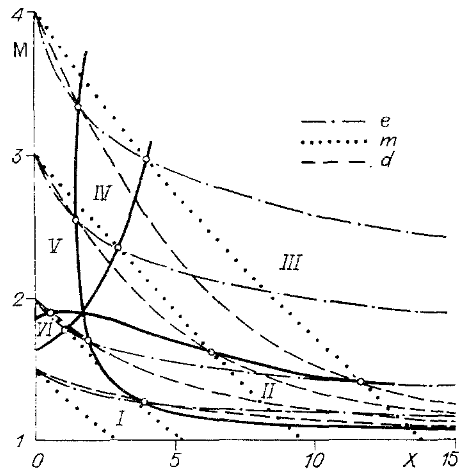

Fig. 1

and is tabulated in [4]. For practical calculations an approximation $G_e(M) \approx 1.58[(M^2 - 1)^2(M^2 + 1/4)^{1/2}]^{-1}$ has been suggested [7], which deviates from the accurate solution of (1.3) by no more than 12% in the range $1.01 \leq M \leq 4$.

Comparison of experimental data [5, 6] shows that Eq. (1.3) gives satisfactory results, at least when the expansion angle of the duct is ≤15°.

2. Attenuating a Shock Wave in a Channel with Perforated Walls. The quasi-one-dimensional equation for the C_+ characteristic when a step shock wave propagates in a channel with perforated walls has the form [8, 9, 13]:

$$\frac{u+a}{a^2}\frac{dp}{dx}+\frac{\rho(u+a)}{a}\frac{du}{dx}=-\varepsilon(\omega\Pi/A)\dot{m}, \tag{2.1}$$

where ε is the "permeability" of the wall (the ratio of the area of the openings to the surface area of the wall); ω is the fraction of the perimeter of the channel occupied by the perforated wall; Π is the perimeter of the cross section of the channel; and $\dot{m}$ is the specific flow rate of gas through an opening. Substituting the jump conditions and the formula for isentropic gas flow with an empirical flow rate coefficient into (2.1) [13] gives the equation for the Mach number

$$g_m dM/dx = -(\omega\Pi/2A)\varepsilon\ ;$$

the solution with $M(0) = M_0$ is

$$G_m(M_0) - G_m(M) = X_m. \tag{2.2}$$

Here $X_m \equiv (\omega\Pi/2A)\varepsilon x$ is the dimensionless shock wave propagation distance in the perforated channel; and $G_m(M) = \int g_m(M)\,dM$. The approximation $G_m(M) \approx 4.3\cdot(M^{1.2} - 1.012)^{0.8}$ does not deviate from the tabulated $G_m(M)$ [13] by more than 5% for $1.01 \leq M \leq 4$.

Comparison [13] of experimental data [8, 9-11] with calculations from (2.2) shows that for $1.1 \leq M \leq 4$ there is good agreement in a wide range of "permeabilities" ($4.5\cdot10^{-3} \leq \varepsilon \leq 0.53$) channel dimensions, and the parameter $\omega = 0.5$-0.1.

3. Attenuation of Shock Waves in a Channel with Barriers and Curtains. When a step shock wave propagates in a channel containing barriers that are hard to flow around, the equation for the C_+ characteristic has the form [18, 29, 30]

$$\frac{u+a}{\rho u^2[(\gamma-1)u-a]}\left[\frac{dp}{dx}+\rho a\frac{du}{dx}\right]=-\frac{f}{2},$$

where f is a parameter (constant at large Reynolds numbers), which characterizes the aerodynamic resistance of a unit thickness of the protective screen. Substitution of the jump

TABLE 1

Number	Shock wave attentuation method	X	References
1	Expanding cross section	$A_0^{-1}(dA/dx)x$	[4—7]
2	Wall perforation	$(\omega\Pi/2A)\varepsilon x$	[8, 9—11, 13]
3	Regular barriers	$(\Pi/2A)\zeta x$	[14, 17, 18, 30]
4	Packed beds [1]	$1{,}75(1-\varepsilon)(\varepsilon d_p)^{-1}x$	[18, 31, 32, 34]
5	Gas suspensions [2]	$0{,}75C_D\rho_p(\rho_p^0 d_p)^{-1}x$	[18, 31, 42, 45]
6	Lattices [3]	$(\pi/8)C_D d_p^2 h^{-3}x$	[18, 31]
7	Porous stemming [4]	$0{,}5\sigma(\rho_p^0 s)^{-1}x$	[18, 31]
8	Perforated barrier [5]	$X_1 = 26(\varepsilon^{-0,1}-1)$	[18, 29, 31]
9	A cascade of n identical barriers [6]	nX_1	[18, 29, 31]

Notes. 1) d_p is the particle dimension, and ε is the porosity of the packed bed; 2) C_D is the aerodynamic drag of the particles as the Reynolds number → ∞, ρ_p is the mass concentration of the particles, and $\rho_p{}^0$ is the density of the particle material; 3) d_p is the dimension of a lattice node, and h is the distance between lattice nodes; 4) σ is the density of the porous material, s is the characteristic dimension of a cell, and $\rho_p{}^0$ is the density of the connecting material; 5) ε is the permeability of the barrier; 6) in the absence of mutual barrier interactions.

conditions gives the equation

$$g_d(\mathrm{M})d\mathrm{M}/dx = -f/2,$$

whose solution for $M(0) = M_0$ is

$$G_d(\mathrm{M}_0) - G_d(\mathrm{M}) = X_d \qquad (3.1)$$

where $X_d \equiv f\cdot x/2$ is the dimensionless propagation distance of a shock wave after it enters the screen. For practical calculations, a convenient approximation of the tabulated [30, 45] function $G_d(M) = \int g_d(M)\cdot dM$ is tabulated [30, 45]. For practical calculations, the approximation

$$G_d(\mathrm{M}) \approx 4\,\frac{0{,}4\mathrm{M}-1}{\mathrm{M}^2-1} + 4\ln(\mathrm{M}^2-1) + 0{,}8\ln\frac{\mathrm{M}+1}{\mathrm{M}-1},$$

is convenient; it does not deviate from the exact solution to (3.1) by more than 5% for $1.01 \le M \le 4$.

Table 1 [18, 30] shows quantities which should be used as the dimensionless distance $X = X_d$ in screens and barriers of various configurations. For example, if the barriers are in the form of regular protuberances on the channel walls, it is recommended [17, 30] that $X_d = (\Pi/2A)\cdot\zeta\cdot x$, where ζ is the hydraulic resistance used when a quadratic resistance law is valid. Table 1 also shows expressions for $X = X_e$ and X_m.

The predictions given by (3.1) have been verified for all the barrier configurations given in [17, 18, 29-31, 34, 45] by comparison with available experimental data. References to the corresponding sources are given in the table. In spite of the different configurations, Eq. (3.1) shows good accuracy.

4. Comparison of Shock Wave Attenuation Methods. Investigating shock wave attenuation methods with a single approach, which reduces uniform finite equations – (1.3), (2.2), and

(3.1) – makes possible a direct comparison of the effectiveness of the protective measures. The effectiveness of the protective measures will be taken to be the ratio $(M_0 - M)/M_0$ which is attained after a given dimensionless distance X. Figure 1 shows a nomograph of the Mach number of the air shock wave as a function of the dimensionless distance X traversed by the wave in the protective screen. The solutions (1.3), (2.2), and (3.1) the tabulated functions $G_e(M)$, $G_m(M)$, and $G_d(M)$ [4, 13, 45] were used in calculating the nomograph. The nomograph contains three families of curves: the dot-dash curves are for shock wave attenuation in expanding channels; the dotted lines are for channels with permeable screens; and the dashed lines are for channels with barriers or suspensions. These curves were calculated for fixed values of $M_0 = M(X = 0) = 1.5$, 2, 3, and 4. The intersection points of the various families of curves (e and m, e and d, and m and d) at the same M_0 are the points of equal effectiveness of the protective measures. This means that the corresponding protective measures give the same shock wave intensity at the same dimensionless distance.

We will call the locus of points of equal effectiveness "lines of equal effectiveness." The solid curves on the nomogram – the lines of equal effectiveness – line in six regions in the M–X plane. In region I, perforating the channel is more effective than expanding the cross section, which in turn is more effective than mounting barriers or curtains; this relationship of effectiveness of the protective measures can be conveniently written in the form m > e > d; for regions II-VI, m > d > e, d > m > e, d > e > m, e > d > m, and e > m > d. The nomograph can be used in practical calculations.

In designing protective measures, it is advisable to start by minimizing the dimensionless distance to attenuate the shock wave. Fixing the physical distance $(x\Pi/2A)_*$ minimizes the effect of the protective measures on the system.

Suppose we must attenuate an air shock from $2.5 < M < 4$ to $M < 1.3$. According to the nomograph, it is better to perforate the channel walls. If $(x\Pi/2A)_* = 100$, the required permeability of the tube walls is $\varepsilon \approx 0.12$. If perforated walls cannot be used for some reason, a shield in the form of barriers or a curtain should be used. In this example, a cascade of regular barriers with a thickness of $(x\Pi/2A)_* = 100$ can be used, which creates a hydraulic resistance $\zeta \approx 0.135$; a cascade of barriers with a thickness of $x\Pi/2A < 100$ can be used, but with a corresponding larger hydraulic resistance [17, 30]. In order to attain the same result, one perforated barrier can be installed with a permeability of $\varepsilon \approx 0.04$ or, for example, five widely spaced barriers, each with $\varepsilon \approx 0.2$ [18, 29, 31]. If clogging the cross section of the channel is not desirable, then expansion of the channel should be examined, but in this case the cross section must be expanded by 1424 times!

Comments. Because shock waves generated by detonating an explosive charge and gas and dust clouds are usually characterized by a pressure drop behind the front, analysis of the attenuation of step shocks gives conservative estimates of their destructive effects.

In practical calculations it must be kept in mind that the method [1, 4] cannot be used to predict the profile of the parameters behind the shock front. In order to analyze the effect of the attenuated shock wave, additional information on the pressure pulse is required [26].

Use of the method [1, 4] to design protective measures has several physical limitations. Test [5] showed that an anomalously high pressure is observed when the shock wave goes from an expanding part of the channel to a part with constant cross section. This is related to shock wave diffraction, which can be considered by a proper correction [5-7]. In calculating the attenuation of shock waves by a gas suspension, it is necessary to consider the possibility of establishing an equilibrium flow of a two-phase fluid [38, 45]. More information on the limits to applying this method is given in [4-6, 13, 17, 18, 29-31, 34, 45].

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