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THE DEPENDENCE OF BLAST ON AMBIENT PRESSURE AND TEMPERATURE

BY

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THE DEPENDENCE OF BLAST ON AMBIENT PRESSURE AND TEMPERATURE

Abstract

The effect of external atmospheric conditions on the blast from an explosive is considered. It is assumed that a change in these external conditions leads only to a change of the scale of pressure, distance, and time. It is further assumed that except for this change of scale the total energy in the blast wave is independent of the external conditions. The result of these considerations is a generalized law of similitude, namely, the blast pressure measured in units of the atmospheric pressure, P, is a function of $\sqrt[3]{P/W}\,R$ and $\sqrt[3]{P/W}\cdot\sqrt{T}\,t$ only, where W is the charge weight, T is the absolute ambient temperature, R is the distance from the explosive, and t is the time after detonation.

This result obtains only if external conditions such as the height above the ground, which acts as a reflecting surface, are scaled properly. If the blast effect of explosives detonated in the neighborhood of airplanes in flight is considered, the absence of ground reflection reduces the effective weight of the explosive by a factor of two. Thus it is found that, if the peak blast pressure at a given distance from the explosive is p at sea level, then the pressure at the same distance from the explosive at an altitude such that the atmospheric pressure has been reduced by a factor π $(\pi > 1)$ is approximately $p' = \sqrt[3]{\pi/2}\, p$. If the absolute temperature of the atmosphere at this altitude is less by a factor θ than the sea level temperature, the ratio of the impulse above sea level to that obtained on the ground is

$$\pi^{1/3}/(\sqrt[3]{4}\sqrt{\theta}).$$

A further result of these considerations is that changes in temperature may lead to a positive impulse under extreme winter conditions which is 8% greater than the positive impulse obtained under extreme summer conditions.

1. Introduction

Interest in the dependence of the blast from high explosives on the atmospheric pressure and temperature has recently been stimulated by attacks with bombs on airplanes in flight. In order to determine the effectiveness of the blast from these bombs, it is necessary to know the peak pressure in the blast and the impulse, i.e., the area under the pressure time curve. However, all measurements of these quantities have been carried out on the ground where the ambient pressure and temperature are considerably higher than those at high altitudes. In order to infer information concerning the blast at high altitudes from the information obtained on the ground, it is necessary to determine the effect of the change in pressure and temperature on the blast.

2. The similarity transformation

A rigorous treatment of the effect of changes in atmospheric conditions on the blast from an explosion would require a detailed discussion of the manner in which the detonation wave in the explosive interacts with the surrounding atmosphere to form a blast wave. However, it seems reasonable to assume that the properties of the blast wave at distances large compared to the dimensions of the explosive do not depend on the details of this process, but that they depend only on the total energy available to the blast and on the external conditions. Then the simplest dependence of the shock wave on changes in the atmospheric pressure and temperature and on the energy available is expressible in terms of a similarity transformation. That is, the dependence of pressure and density of the air in the blast on distance and time for one set of external conditions may be obtained from that for different external conditions by changing the scale by which pressure, density, distance, and time are measured. The magnitude of the change in scale is uniquely determined by the change in external conditions, as will be shown subsequently.

The pressure in the blast wave may be expressed as a function $p(R,t)$ of distance, R, from the explosive and time, t, after the explosion for given atmospheric pressure P and absolute temperature T. If the atmospheric pressure and temperature are changed to $P' = \pi P$ and $T' = \theta T$, then, according to the law of similitude, the new blast pressure $p'(R',t')$ at distance $R' = \chi R$ and $t' = \tau t$ is given by

$$p'(R',t') = \pi p(R,t)$$

where χ and τ are constants which determine the change in scale of distance and time. When $p(R,t)$ is a solution of the equations of motion of the blast wave, then $p'(R',t')$ is also a solution* if the scaling constants x, τ, and θ satisfy the relation

$$x/\tau = \sqrt{\theta} . \qquad (1)$$

The new solution has the required properties that the blast pressure at great distances from the explosive approach the value $p' = \pi P$ and that the velocity of the shock wave at great distances be equal to the velocity of sound in air at temperature T'. Actually, the condition Eq. (1) follows from the latter requirement since the velocity of sound is proportional to the square root of the absolute temperature and, in addition, it must have the dimensions of distance divided by the time.

The energy that goes into the blast wave will be defined as the total energy of the air behind the shock front, less the energy of the same volume of air at atmospheric conditions. Thus the energy, E(t), at any time t after the explosion may be written as

$$E(t) = \int [p + 1/2\,\rho u^2 + \rho \int_0^T C_v\, dT]\, dV$$

$$-(p_o V + \rho_o C_{vo} T_o V),$$

where ρ is the air density, u the velocity of mass motion, and C_v the specific heat at constant volume per unit mass. The volume integration is to be carried out over the volume, V, behind the shock front. The subscript o refers to atmospheric conditions.

When the atmospheric conditions are changed the first term in the energy is multiplied by πx^3 since it has the dimensions of pressure times distance cubed. From their dimensions, it is clear that the other terms must change in the same way**; so the energy, E, under the one set of conditions at time t is related to the energy, E', under the other conditions at the corresponding time t' by

$$E'(t') = \pi x^3 E(t).$$

* See appendix.

** This can be verified directly for the $1/2\rho u^2$ term by means of the formulae given in the appendix. It is also immediately clear for the specific heat term if the air may be treated as a perfect gas.

It will be assumed that the energy depends only on the mass and nature of the explosive and that it is independent of external conditions. Then if the mass of the explosive is increased by a factor m, the available energy is increased by the same factor. It follows that $\pi x^3 = m$ or

$$x = \sqrt[3]{m/\pi} . \qquad (2)$$

Combining this result with Eq.(1), the change of time scale is found to be

$$\tau = \sqrt[3]{m/\pi} \cdot 1/\sqrt{\theta} . \qquad (3)$$

The results contained in Eqs.(2) and (3) can be expressed in terms of a generalized law of similitude: if P and T are the atmospheric pressure and (absolute) temperature and if W is the weight of the explosive, the blast pressure measured in units of P is a function of $\sqrt[3]{P/W} \cdot R$ and $\sqrt[3]{P/W} \cdot \sqrt{T}\, t$ only. Expressed analytically,

$$p/P = f(\sqrt[3]{P/W}\, R,\ \sqrt[3]{P/W}\, \sqrt{T}\, t). \qquad (4)$$

This result is applicable only as long as other external conditions such as the position of the explosive relative to the ground are scaled properly. The effect of these factors will be considered in Section 3.

The special case of the law of similitude for which the atmospheric conditions are kept constant and only the weight is varied has been verified experimentally within reasonable limits (less than 10%) in a range of explosive weights from 1 to 20,000 lbs.

3. Influence of the ground surface on similitude

In comparing the blast from explosives of various sizes some deviations from the results of the foregoing section may be expected because of the loss of energy due to friction between the blast wave and the ground. For increasing charge weights or decreasing atmospheric pressures and temperatures the absolute distance from the explosive at which a given energy should be observed increases. Therefore the distance over which frictional effects can act increases and the available energy correspondingly decreases. Thus the pressures may be expected to be somewhat smaller than expected from similitude considerations under these circumstances.

In order to maintain similitude it is necessary to scale the height of the explosive above the ground in accordance with Eq.(2). Otherwise the amount of energy lost by crater formation will not scale and the position of any reflected shock wave with respect to the primary shock wave will not scale. The effect of the position of a reflected wave can probably be minimized by going to distances from the explosive great enough to give the shock wave a chance to become smooth.

The fact that the scaling with change in weight of explosive has been experimentally verified within about 10% indicates that these deviations are small insofar as blast measurements on the ground are concerned. However, in comparing the blast at high altitudes with the blast observed from the same type of explosive on the ground, they can no longer be neglected. In the usual case the high altitude explosion will not take place in the presence of a reflecting surface such as the ground. If the ground were a perfectly reflecting surface the average energy density in the ground level blast would be twice as great as that in the high level case since in the former the energy is distributed over a hemisphere while in the latter it is spread over a sphere. If the blast is observed at a distance great enough for the reflections to be smoothed, the scaling may be expected to apply but with the effective weight of charge half as great for the high altitude case to take account of the difference in energy density*. Thus Eq. (2) becomes

$$x = \sqrt[3]{m/2\pi}, \qquad (5)$$

and Eq. (3) becomes

$$\tau = \sqrt[3]{m/2\pi} \cdot 1/\sqrt{\theta}\,. \qquad (6)$$

Actually the ground is not a perfectly reflecting surface and the loss of energy due to friction and crater formation will tend to increase the factor $1/\sqrt[3]{2}$ appearing in Eqs. (5) and (6) to a value more nearly equal to one. Since the precise effect of these factors cannot be determined at present, use will be made of Eqs. (5) and (6) as they stand.

* It should be pointed out that if the shock wave is sufficiently intense it will form a Mach wave on reflection from the ground whereas no such distortion of the shock wave will occur at high altitudes. This may invalidate the scaling between the high level and sea level explosives, but it is felt that a quantity obtained by averaging, such as the positive impulse, will continue to scale.

4. Dependence on altitude of peak pressure and impulse at a given distance.

A particular application of Eqs. (5) and (6) is to determine the peak pressure and impulse at a fixed distance, R, from a bomb detonated above sea level when the values of these quantities are known at this distance from the same type of bomb at sea level. The relation between peak pressure and distance at sea level is approximately

$$p = k/R^n$$

where k is a constant and n is a number between 1 and 2. The corresponding relation at such an altitude that the pressure and temperature are reduced by factors π and Θ respectively is

$$p' = X^n \pi k/(R')^n \ .$$

Thus for $R' = R$, $p' = X^n \pi p$, or making use of Eq. (5) and setting $m=1$:

$$p' = \pi^{1-n/3}/2^{n/3} p. \qquad (7)$$

For peak pressures less than one atmosphere, n is approximately 1.5 so

$$p' = \sqrt{\pi/2}\, p. \qquad (8)$$

Thus the blast pressure at an altitude of 25,000 feet, where the atmospheric pressure is reduced by a factor 3, is approximately $1/\sqrt{6} = 0.41$ times the pressure measured at sea level at the same distance from the bomb.

The change in the positive impulse can be treated similarly. Since the impulse has the dimensions of pressure multiplied by time, its scaling factor is $\pi\tau$. The dependence of positive impulse on distance at sea level is approximately

$$I = I_0/R \ .$$

Thus at high altitudes the impulse-distance relation is

$$I' = \pi \tau X \, I_0/R' \ .$$

For $R' = R$ this becomes $I' = \pi^{1}xI$, making use of Eqs. and (6),

$$I' = \pi^{1} \sqrt[3/4]{} \sqrt{\theta}\ I. \qquad ( )$$

For the example considered [illegible] the previous paragraph, the temp[illegible]erature is reduced by a fac[illegible]r of 0.81 (assuming a sea level temperature of 20°C) so the impulse is reduced by a factor of 0.48.

5. Effect of variations of [illegible]emperature on blast measurements

In carrying out blast m[illegible]urements on bombs there are day-to-day variations in the atmos[illegible]ric pressure and temperature. A corresponding change in the [illegible]served blast is to be expected. The difference in the result[illegible] to be expected from one day to another are determined by E[illegible](2) and (3) if π is the ratio of the pressures on the two da[illegible] and θ is the corresponding ratio of absolute temperatures. [illegible] general the relative variation in pressure is small and it ma[illegible] assumed that π=1. [illegible] given weight are considered, [illegible] follows from Eq.(2) that x=1. On the other hand, the tempe[illegible] [illegible] between 35°C and -10°C between summer and winter du[illegible] tests carried [illegible] Ballistic Research Laborator[illegible]. This corresponds to a change of 16% in the absolute temperature so that a temperature effect is to be expected.

Inserting x=1 in Eq.(1), the relation

$$\tau = 1/\sqrt{\theta}$$

is obtained. Therefore, if the positive impulse time in summer is t, the positive impulse time in winter is $t' = (1/\sqrt{\theta})t$ where θ is the ratio of winter to summer temperature. In the case considered in the preceding paragraph, the extreme variation of positive impulse time would be 8%. Since the peak pressures are unaffected by the temperature change, a corresponding change in positive (or negative) impulse is to be expected. Thus the positive impulse observed in winter may be as much as 8% greater than that observed in summer for the same type of bomb.

This problem has been discussed with Drs. H. Lewy, J. E. Mayer and S. Chandrasekhar, and many of their suggestions have been incorporated in its treatment.

R. G. Sachs

R. G. Sachs

APPENDIX

The differential equations determining the pressure p, density ρ, and the gas velocity $\vec{u}$ of the air are the cont[illegible] equation:

$$\mathrm{div}\ \rho\vec{u} + \partial\rho/\partial t = 0, \qquad (a)$$

and the force equation:

$$\rho\ d\vec{u}/dt + \mathrm{grad}\ p = 0. \qquad (b)$$

The function u(R,t) becomes

$$\vec{u}'(R',t') = \frac{X}{\tau}\,\vec{u}(R,t)$$

under the new conditions since u has the dimensions of len[illegible] divided by time. ρ is proportional to p/Γ so it becomes

$$\rho'(R',t') = \frac{\pi}{\theta} \cdot \rho(R,t)$$

Substitution of these relations and the corresponding rela[illegible] for p'(R',t') in Eqs. (a) and (b) leads to the equations

$$\frac{\theta}{\pi} \cdot \tau\ \mathrm{div}'\ \rho'\ \vec{u}' + \frac{\theta}{\pi} \cdot \tau \frac{\partial\rho'}{\partial t'} = 0,$$

and

$$\frac{\theta}{\pi} \cdot \frac{\tau^2}{X} \cdot \frac{d\vec{u}'}{dt'} + \frac{X}{\pi}\ \mathrm{grad}'\ p' = 0,$$

where div' and grad' imply differentiation with respect to new variables R' = XR and t' = τt. The first of these eq[illegible] has the same form as Eq. (a) as required and the second re[illegible] to Eq. (b) in virtue of the condition Eq. (1). Therefore ρ', u' are solutions of the differential equations. Wheth[illegible] they are the correct solutions can only be determined by sh[illegible] that all boundary conditions scale in the same way. [illegible] apparent for the boundary conditions referring to large va[illegible] of R but nothing can be said about the conditions at R=0 wi[illegible] further knowledge of the interaction of the detonation wave [illegible] the air.

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The dependence of the effectiveness of the blast from an explosive on ambient pressure and temperature was investigated in order to infer information concerning the effectiveness of the blast at high altitudes from the information obtained on the ground. Assuming that a change in external atmospheric conditions leads only to a change of the scale of pressure, distance, and time, a generalized law of simulitude is derived. The expression is applicable only if external conditions such as the position of the explosive relative to the ground are scaled properly. The absence of ground reflection reduces the effective weight of the explosive by a factor of two. Changes in temperature may lead to a positive impulse under extreme winter conditions which is 8% greater than the positive impulse obtained under extreme summer conditions.

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