AIAA 81-4165

Gun Firing Similarity for Aircraft Interference Problems

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Introduction

THE effects of gun firing are generally studied in installations which are expensive to both build and use. This is especially true for large-bore weapons. Moreover, for aircraft guns the airflow around the plane cannot be neglected, particularly at high angles of attack; therefore, flight tests must be made which are both very expensive and sometimes difficult to understand. For these reasons, the interest in a simulation in wind tunnels with small caliber guns becomes manifest.

Our purpose is to provide similarity rules which enable representation of these phenomena with a model in a wind tunnel. Similarity will be restricted to the blast waves which follow firing; the complex phenomena occurring at the muzzle before the appearance of blast waves will not be considered.

A Schematic Analysis of the Problem

The phenomena which take place after a gun firing have already been analyzed in numerous papers (see, for instance, Refs. 1-4). We shall briefly describe here only those phenomena valid for weapons of small and intermediate caliber.

The motion of the bullet inside the barrel yields a compression of the air and the birth of a shock wave. When this wave emerges it becomes quasispherical, (called the percursor). Then, as soon as the bullet leaves the gun, the powder gases spread out and give birth to a blast wave. This wave is also quasispherical, but it is much stronger than the precursor so it quickly overtakes and absorbs it. That means that the precursor can be neglected in a first approximation analysis.

The pressure perturbations induced by the bullet are very weak in comparison to those of the blast wave and they can also be neglected. Moreover, for some time after main blast formation, the powder-gas overexpanded jet formed by the emptying of the barrel is almost steady. The properties of the gases at the muzzle can thus be considered as constant during a sufficiently long time.

Let p, ρ, T, c, h, u, and M be the pressure, density, temperature, sound velocity, specific enthalpy, fluid velocity, and Mach number, respectively. D is the bore diameter. The subscript 0 is reserved for the muzzle state. In a first approximation it is assumed that the powder gases are perfect, of specific heat ratio γ.

During gun emptying the muzzle represents a source of mass, momentum, and energy. The balance of these quantities in the conservation laws introduces

$$\rho_0 u_0 D^2,\ (p_0+\rho_0 u_0^2)D^2,\ \text{and}\ (h_0+u_0^2/2)\rho_0 u_0 D^2$$

which may be replaced by

$$\gamma M_0 p_0 D^2/c_0,\ (1+\gamma M_0^2)p_0 D^2,\quad \text{and}$$

$$(\gamma/\gamma-1+\gamma M_0^2/2)M_0 c_0 p_0 D^2$$

Obviously a firing is characterized by the four parameters γ, M_0, c_0, and p_0D^2. It must be observed that the bore diameter D appears only in the group p_0D^2 and not separately.

Received Feb. 20, 1981.

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Gun Firing Similarity

Let us consider at first a gun firing in an infinite, stagnant atmosphere (subscript 1). The new quantities to be taken into account for similarity are γ_1, p_1, and ρ_1 (of course, p_1 or ρ_1 can be replaced by T_1 or c_1). Thus, each local property is a function of γ, M_0, c_0, p_0D^2, γ_1, p_1, and ρ_1, of the position $\vec{x}$, and of time t, the origin of which can be taken at shot uncorking. One obtains for the pressure, for instance

$$\frac{p}{p_1}=\mathfrak{F}\left[\gamma,\gamma_1,M_0,\frac{T_0}{T_1},\left(\frac{p_1}{p_0}\right)^{1/2}\frac{\vec{x}}{D},\left(\frac{p_1}{p_0}\right)^{1/2}\frac{c_1 t}{D}\right]$$

It is to be noticed that neither D nor p_0 appear in the similarity conditions which express the invariability of γ,γ_1,M_0, and T_0/T_1. When these conditions are fulfilled, at points and at moments for which $(p_1/p_0)^{1/2}\vec{x}/D$ and $(p_1/p_0)^{1/2}c_1t/D$ are constant, the ratio p/p_1 has the same value.

If the air is moving with velocity u_1 (as in the case of an airplane), a new usual condition must be satisfied, that is the invariability of the Mach number $M_1=u_1/c_1$.

Let us now assume that firing occurs in the vicinity of a body of characteristic length L. The problem now involves the new datum L and, as a consequence, to the similarity conditions concerning γ, $\gamma_1,M_0,T_0/T_1$, and M_1 we must add the condition $(p_1/p_0)(L/D)^2=\text{const}$.

So we see that the caliber D and pressures p_0 and p_1 appear in the similarity conditions only when the firing occurs in a limited field. It may be emphasized that the scale of the body and that of the bore can be different, which is very interesting from a practical point of view, as will be shown below.

Generalization for Nonperfect Propellant Gases

The propellant gases are a mixture of perfect reactant gases (H_2O, CO_2, CO, H_2, N_2...).

At the moment when the blast wave is formed, almost the whole of the gun powder is burned. There remains only some solid particles; the modification in the composition of the mixture and in the heat transfers they yield when they pass the muzzle will be neglected. Thus, we can consider that combustion is completely accomplished when the blast wave appears.

Inside the gun the evolution of the mechanical properties is slow compared to that of the chemical reactions which can be considered as instantaneous. That means that the composition of the gaseous mixture and its thermodynamic properties depend only on temperature and pressure.

The foregoing is not valid in the overexpanded jet where pressure and temperature change very rapidly. There, mechanical and chemical effects are coupled and irreversible processes take place which can have some influence on the energy balance.

Any change in a gaseous mixture at chemical equilibrium can be expressed as a function of two state variables and of three partial derivatives of thermodynamic parameters.[5] Let us take for these five quantities p, T, the specific heat at constant pressure $C_{p_e}=(\partial h/\partial T)_p$, $D_T=(\partial \log n/\partial \log T)_p$, and $D_p=(\partial \log n/\partial \log p)_T$. Here n is the specific number of moles of the mixture and the subscript e refers to equilibrium.

As the different components of the propellant gas are perfect, the state equation of the mixture is $p=rn\rho T$ where r is the well-known universal constant.

Taking these facts into account, we can write $h=\tilde{Q}_f+C_{pf}(T-\tilde{T})$. In this formula $\tilde{T}$ is a standard temperature and $\tilde{Q}_f$ the heat of formation of a frozen mixture having the same composition as the propellant gas at this temperature. C_{pf} is the specific heat taken at constant pressure and composition: $C_{pf}=(\partial h/\partial T)_{p,n}$.

As a consequence, in the conservation laws expressed at the muzzle we find the parameters C_{pe}, D_p, D_T, rn, p_0D^2, c_0, $\tilde{Q}_f$, T_0, $\tilde{T}$, C_{pf}, and M_0. But, as $\tilde{T}$ has an arbitrary value, it can be cancelled.

As the problem is no longer purely mechanical, there are now four fundamental quantities instead of three. Six thermodynamic parameters appear in our new formulation. Consequently, there are five similarity conditions related to the thermodynamic state. This means that similarity conditions are the same as those for a perfect gas, but γ must be replaced by the set of thermodynamic dimensionless parameters

$$G=\{C_{pe}/C_{pf},D_p,D_T,rn/C_{pf},\tilde{Q}_f/C_{pf}T_1\}$$

C_{pe}/C_{pf} characterizes the chemical state of the mixture and rn/C_{pf} and $\tilde{Q}_f/C_{pf}T_1$ show the influence of its composition.

As an example, let us assume that the gases are almost frozen. Then we have $D_p\simeq 0$, $D_T\simeq 0$, $C_{pe}\simeq C_{pf}$, and $\tilde{Q}_f/C_{pf}T_1\simeq\tilde{T}/T_1$ as arbitrary quantities without influence on the phenomenon. Only one parameter remains, rn/C_{pf}, which is equal to $\gamma-1/\gamma$, so that we find the same thermodynamic condition as for a perfect gas.

As we see, the generalization concerning the thermodynamic state does not affect the important result about the independence of the model and the gun scales. Nevertheless, the generalization points out the dependence between T_0 and p_0 and the set of thermodynamic parameters: thus, the similarity conditions may become more difficult to satisfy.

Application to Gun Firing in Wind Tunnels

In order to show the validity of previous results we apply them to gun firing tests with models in a wind tunnel.

Let $G, p_0, \rho_0, D...L$ refer to the wind tunnel and $G', p_0', \rho_0', D'...L'$ to the flight. Among the similarity conditions some are classical: air is used in both cases ($\gamma_1=\gamma_1'$) and it is usual to achieve $M_1=M_1'$. If the shot exit velocity is not too high, the flow at the muzzle is sonic ($M_0'=M_0=1$). Finally, if the chemical effects have little influence on the blast wave, the thermodynamic similarity conditions reduce to $\gamma=\gamma'$. This can easily be realized by using the same gunpowder. Thus, only two conditions remain:

$$\frac{T_1}{T_1'}=\frac{T_0}{T_0'}\ \text{and}\ \frac{p_1}{p_1'}\left(\frac{L}{L'}\right)^2=\frac{p_0}{p_0'}\left(\frac{D}{D'}\right)^2$$

Now, we have

$$p_i=p_1\left(1+\frac{\gamma_1-1}{2}M_1^2\right)^{(\gamma_1/\gamma_1-1)},\quad T_i=T_1\left(1+\frac{\gamma_1-1}{2}M_1^2\right)$$

$$p_1'=p_sA(z),\qquad T_1'=T_sB(z)$$

where p_i and T_i are the stagnation pressure and temperature of the wind tunnel, p_s and T_s the pressure and the temperature on the ground, z the flight altitude, and $A(z)$ and $B(z)$ the pressure and temperature distributions in the atmosphere.

Our conditions become

$$\frac{T_i}{T_s}=\left(1+\frac{\gamma_1-1}{2}M_1^2\right)\frac{T_0}{T_0'}B(z)$$

$$\frac{p_i}{p_s}\left(\frac{L}{L'}\right)^2=\left(1+\frac{\gamma_1-1}{2}M_1^2\right)^{(\gamma_1/\gamma_1-1)}\frac{p_0}{p_0'}\left(\frac{D}{D'}\right)^2A(z)$$

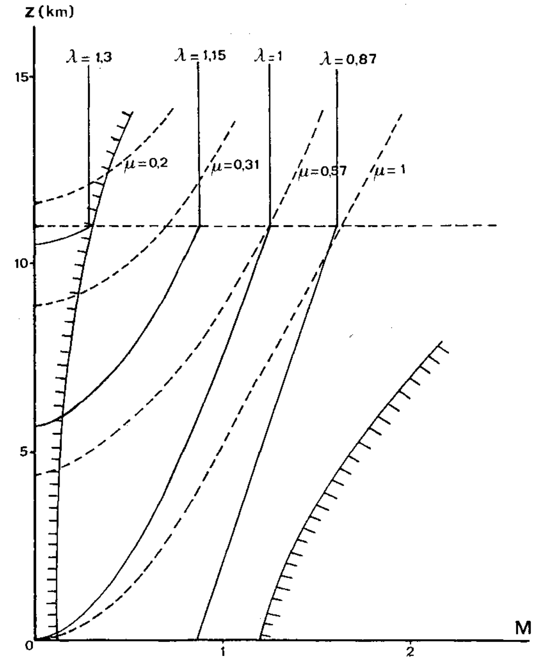

Fig. 1 Effect of changing parameters λ and μ.

These conditions must be satisfied over the whole flight domain. For given M_1 and z this may be done by changing either separately or simultaneously the bore of the simulation gun or its gunpowder charge, the scale of the model, and the stagnation values p_i and T_i.

Figure 1 shows how it is possible to cover the flight domain of a military airplane by changing the parameters

$$\lambda=\frac{T_i}{T_s}\frac{T_0'}{T_0}\quad\text{and}\quad\mu=\left(\frac{L}{L'}\frac{D'}{D}\right)^2\frac{p_i}{p_s}\frac{p_0'}{p_0}$$

For standard atmosphere our conditions give two families of curves corresponding to constant values of λ and μ. Each point of intersection of two curves, λ and $\mu=$const, defines the relations which have to be fulfilled between $T_i, T_s, T_0', T_0, L, L', D, D', p_i, p_s, p_0'$ and p_0.

Let us give an example for a wind tunnel using atmospheric air ($p_i=p_s, T_i=T_s$). We suppose that the propellant gases are perfect and we fix $D'/D=4$, $L'/L=8$, and $M_1\leq 0.4$. Then we must have at our disposal a set of simulation guns allowing p_0/p_0' and T_0/T_0' to vary between 0.25 and 1.25 and between 1.0 and 1.3, respectively.

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