Wind-Tunnel Simulation of Store Jettison with the Aid of an Artificial Gravity Generated by Magnetic Fields

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In this paper a set of model scaling equations for wind-tunnel simulation of the trajectory of jettisoned stores from aircraft is presented. This scaling is based upon a scaled gravitational acceleration. It is shown that a suitable scaled gravity can be developed by means of magnetized ferromagnetic spheres in a magnetic field gradient. Preliminary experimental results are presented that illustrate that "gravity can be modified" by this technique.

Nomenclature

B = magnetic field strength
B_z = vertical component of **B**
C_F = force coeff
C_P = moment coeff
F = aerodynamic force
H_{zM} = magnetic flux for magnetization
H_{zG} = magnetic flux for gradient
I = moment of inertia
L = length
M = Mach number
M = magnetization of model
M_z = vertical component of magnetization of model
N = length scale factor = full-scale dimension/model dimension
$\overline{NI}$ = ampere turns in magnetizing or gradient coil
P = aerodynamic moment
S = reference area
T = static temperature of air
V = velocity
W = weight
g = acceleration of gravity
h = test section height or coil radius
k = radius of gyration
p = static pressure of freestream
q = dynamic pressure
s = specific density of model
x = distance along trajectory
z = vertical component of distance along trajectory
α = angle of attack
γ = trajectory angle with respect to horizontal reference
θ = angle of rotation
ρ = density of air
ω = angular velocity

Subscripts

$(\ )_f$ = full scale
$(\ )_m$ = wind-tunnel model

Introduction

ALTHOUGH it is not uncommon in aircraft operations to jettison external or internal stores, development of the actual jettisoning procedure is complicated. The reason for this lies in the problems of dynamic simulation of the jettisoned store's trajectory. Simulation of this trajectory in low-speed flow is straightforward because in this case it is sufficient to fix the velocity scale in terms of the scaled time for the store to fall its own length.[1] At higher speeds, where the Mach number of the store becomes important, the scaling requirement is complicated because the time for acoustic impulses to propagate the length of the model must also be scaled. By analyzing the requirements for scaling, assuming that gravity is the same for both the model and the full scale store, two distinct types of processes evolve.[2] First, by assuming that velocity scaling is more important than Mach number scaling, a procedure is developed that gives rise to lightweight models. Second, by assuming that Mach number scaling is important, a procedure is developed that gives rise to heavyweight models. Both these procedures have deficiencies.

The lightweight models have relatively large accelerations due to aerodynamic forces in comparison with the gravity; hence, in a given time interval the store falls too short a vertical distance in comparison to its rearward displacement. Thus the store may strike the aircraft in a wind-tunnel test, but not strike the aircraft in the actual case. This shortcoming may be overcome by imparting an initial vertical velocity to the store, or as suggested in Ref. 2, by moving the model of the aircraft upwards at such a rate that the vertical distance between the store and the aircraft is scaled properly. In the heavyweight models the converse is true; that is, the vertical acceleration is correctly scaled but the aerodynamic forces and accelerations are too small. The relevant angular velocities produced by such a model are also too small. Hence, the heavyweight model store falls relatively too fast, so that it may clear the model of the airplane in the wind tunnel, but not in free flight. Note that the procedure suggested in Ref. 2 could be extended to a downward-moving model to again give the proper simulation of the vertical separation distance. The idea of imposing a vertical velocity upon the lightweight store has been extended to include the scaling of the energy required to impart the desired vertical motion.[3]

Note that the information used for the decision about the jettison procedure must include results from both the heavyweight and the lightweight models. In most practical cases movement of the aircraft model is essential to provide positive results. Alternatively, the forces and moments acting on the store in the neighborhood of the aircraft can be measured by supporting the model on an internal balance. These measured forces and moments are used to compute the store trajectory.[4,5] Nevertheless the simulation problem in the wind tunnel is made difficult because the gravitational acceleration is the same for model and fullscale article. Assuming that gravity can be scaled allows not only for simulation of the trajectory of the store center of gravity in the wind tunnel, but also for the pitching motion about the center of gravity. Lack of simulation is due to the difference in Reynolds number between the flight and the model situation. This limitation is no different than that encountered in conventional wind-tunnel testing, but is harder to interpret in the final result. Nevertheless, the use

Received February 7, 1966; revision received August 29, 1966. The author is indebted to E. Silagi and J. Hawkes for their assistance in carrying out the preliminary experiments. Without their efforts and enthusiasm, the preliminary experiments would not have been completed.

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of "pseudo-gravity" allows for closer simulation than has previously been possible. After the scaling laws are introduced, the method of developing the desired body force will be described.

Derivation of Scaling Laws

It is assumed that the full-scale store is N times the wind-tunnel model in each linear dimension. It will be shown that the velocity and time scales can be set in terms of the pseudo-gravitation and the Mach number. The time and velocity scales will be determined so that in their own time scale the model and free flight article will each have fallen the same number of model lengths.

1. Length Scale

By definition the length scale is

$$L_f = NL_m \tag{1}$$

where the subscript f denotes the free-flight state and the subscript m denotes the model condition. Thus, at corresponding points on the trajectories,

$$z_m/L_m = z_f/L_f \tag{2}$$

2. Time and Velocity Scale

By hypothesis the Mach numbers are equal; thus, since

$$M_m = M_f \tag{3}$$

the velocity scale is

$$V_m/V_f = [T_m/T_f]^{1/2} \tag{4}$$

because the speed of sound is proportional to the square root of the static temperature T. In free fall

$$V_m t_m/V_f t_f = L_m/L_f = 1/N$$

Hence, the time scale is

$$t_m/t_f = 1/N \cdot [T_f/T_m]^{1/2} \tag{5}$$

3. Gravity Scale

The distance each store will fall vertically in its gravitational field is $Z = \frac{1}{2} gt^2$; thus, from Eq. (2)

$$z_m/L_m = g_m t_m^2/L_m = g_f t_f^2/L_f = z_f/L_f \tag{6}$$

Hence

$$g_m/g_f = (L_m/L_f) \cdot (t_f^2/t_m^2) \tag{7}$$

By substitution from Eq. (5),

$$g_m/g_f = N(T_m/T_f) \tag{8}$$

Note that although T_f is generally greater than T_m, N is a large number. Thus the model "gravity" must generally be greater than actual gravity. A method for increasing gravity is discussed below.

4. Mass Scale

The mass scale is selected in terms of acceleration by aerodynamic forces, which are dependent upon the angle of attack; that is

$$\alpha = \left.\frac{\dot{z}}{V}\right)_f = \left.\frac{\dot{z}}{V}\right)_m \tag{9}$$

Thus, since

$$(F/m) = qS/m \cdot C_{F\alpha}(\dot{z}/V)$$

one finds

$$(\rho_m S_m/m_m) = (\rho_f S_f/m_f)N$$

Thus the mass scale becomes

$$m_m/m_f = (\rho_m/\rho_f) \cdot (1/N^3) \tag{10}$$

Note $C_{F\alpha}$ is a dimensionless aerodynamic coefficient.

5. Inertia Scale

In a similar way, establishing the requirement that the pitch angles are equal, i.e.,

$$\theta_m = \theta_f \tag{11}$$

the inertia scale can be evaluated in terms of response to aerodynamic moments;

$$\theta_m = \frac{P_m}{I_m}\frac{t_m^2}{2} = \frac{P_f}{I_f}\frac{t_f^2}{2}$$

where I is the moment of inertia and P is the aerodynamic torque.

$$\begin{aligned} I_m I_f &= P_m t_m^2/P_f t_f^2 \\ \text{oe} \quad I_m/I_f &= (1/N^5)(\rho_m/\rho_f)(T_f/T_m) \end{aligned} \tag{12}$$

Note that the ratio of radii of gyration are

$$k = [I/m]^{1/2} \qquad k_m/k_f = 1/N \tag{13}$$

Thus the mass distribution is similar in the model and in the flight article.

6. Angle Scales

By the definition given in Eqs. (9) and (11) it is shown that $\theta_m = \theta_f$ and $\alpha_m = \alpha_f$; thus the flight path angle γ, which is

$$\gamma = \theta - \alpha \tag{14}$$

is also equal in both model and flight conditions. Thus Eq. (14) is compatible with Eq. (2).

The remaining quantity to discuss is the reduced frequency $\dot{\theta}l/2V$, or if $\dot{\theta}$ is replaced by the rolling velocity, the reduced roll helix angle.
Defining

$$\dot{\theta} = P_f/I \tag{15}$$

it is found that

$$\dot{\theta}_m l_m/2V_m = \dot{\theta}_f l_f/2V_f \tag{16}$$

Thus not only is the motion of the center of gravity simulated, by introducing reduced gravity, but the angular motion about the center of gravity is also simulated.

Simulation of Gravity

The key to the simulation proposed here is the artificial gravity. This gravity is developed by a magnetic field and a spherical, soft iron element located at the center of gravity of the model constructed from nonmagnetic material. The soft iron sphere is magnetized by a vertical uniform field of about 5000 oersteds so that the axis of magnetization of the

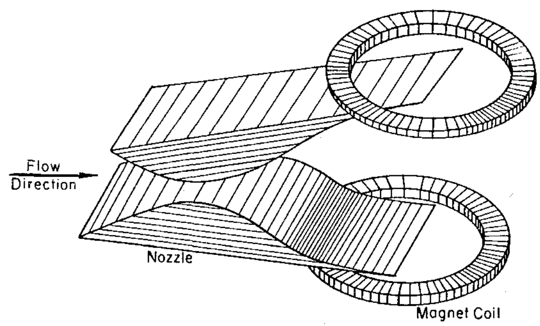
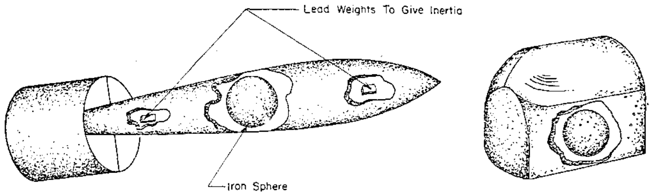


Fig. 1 Arrangement of coils and nozzle.



a) Bomb b) Escape capsule

Fig. 2 Typical models.

sphere is in the gravity direction. Since the element is a sphere, the direction of the magnetization vector is essentially independent of the angular motion of the sphere. The force is generated by a gradient of magnetic field, i.e.,

$$\mathbf{F} = (\mathbf{M}\cdot\nabla)\mathbf{B} = M_z(\partial B_z/\partial z) \tag{17}$$

Note that this is a volume force such as gravity. The arrangement is shown in Fig. 1.

The coils have a radius equivalent to the tunnel height, e.g., h. If NI ampere-turns flow in each magnetizing coil,

$$H_{zM} \simeq 0.7(\overline{NI}/h) \tag{18}$$

A field due to 5000 oersteds will result in a 15,000 gauss field

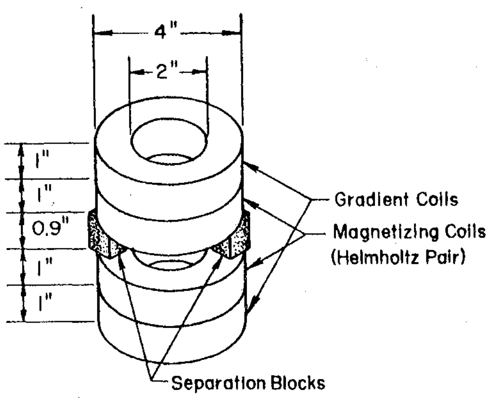


Fig. 3 Coil configuration.

in a sphere, because of its demagnetization factor of $\frac{1}{3}$. A similar set of coils, with the current in the upper coil flowing opposite to the current flow in the lower coil, will cause a gradient

$$\partial H_{zG}/\partial z \simeq 0.7(\overline{NI}/h^2) \tag{19}$$

The gradient coils will have no magnetic field at the center and the gradient field will be generally small compared to the magnetizing field even at the coil. Further, the 15,000 gauss field is essentially at the saturating level, and the gradient fields will not have an appreciable effect on the magnetization level.

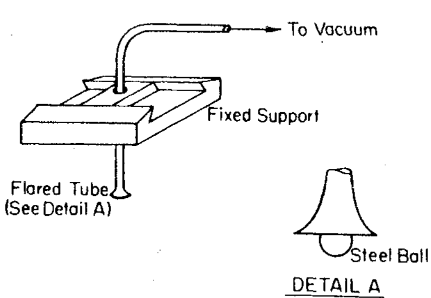


Fig. 4 Apparatus used to hold steel ball in magnetic field.

Fig. 5 Stroboscopic photograph of ball falling under gravity.

Equation (8) may be used to calculate the ratio of acceleration, i.e., if $N = 100$, and $Tf/Tm = 4$,

$$g_m/g_f \simeq \tfrac{100}{4} \simeq 25$$

Thus a 25 g, acceleration must be imposed on the model. Hence, if for this calculation we calculate 25 g,

$$M_z(\partial H_z/\partial z) = 25.980\ S$$

$$\partial H_z/\partial z \simeq 1.5\ S \quad \text{(gauss/cm)}$$

$$\simeq 45\ S \quad \text{(gauss/ft)}$$

For a 2-ft tunnel this means that H_{zG} is about 90 S gauss (S is in grams/cm^3) which will be less than 500 gauss at each gradient coil. Consequently, less than 500 kw of d.c. power are required to generate the artificial gravity in this example. This power is a small fraction of the 5000–10,000 kw needed to drive a $1\frac{1}{2}$- × 2-ft. supersonic tunnel. Typical models are sketched in Fig. 2. In any particular case it may be desirable to trade off magnetization for gradient. Naturally the final adjustment of the artificial gravity could be found experimentally.

Conclusion

It is shown that, if an artificial gravity is imposed by using magnetic fields, the trajectory of a jettisoned store can be approximated quite well. Since the useful volume of the magnetic field generated by the Helmholtz coils is comparable to the volume of the test section, the simulated trajectory is accurate over most of the aerodynamic test section in the tunnel. Finally, note that the temperature ratio of the gas (T_m/T_f) is assumed fixed by external requirements and that this restriction really defines the scaling laws. It is possible to make other assumptions that give rise to different restrictions and derive a totally different set of scaling equations.

Appendix: Results of Preliminary Experiments

Some preliminary experiments were conducted that demonstrate the feasibility of the proposed magnetic technique. The principal purpose of these experiments is to show that a useful volume of uniform acceleration is attainable. The coil configuration is shown in Fig. 3. No attempt was made to

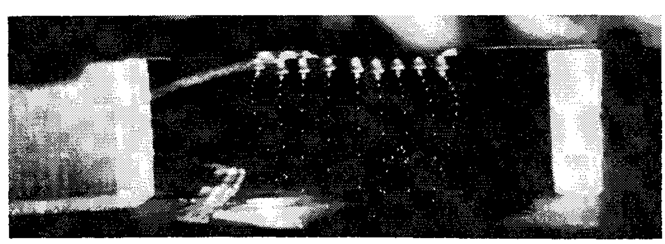


Fig. 6 Stroboscopic photograph of ball falling under gravity and magnetic field at about "½" acceleration.

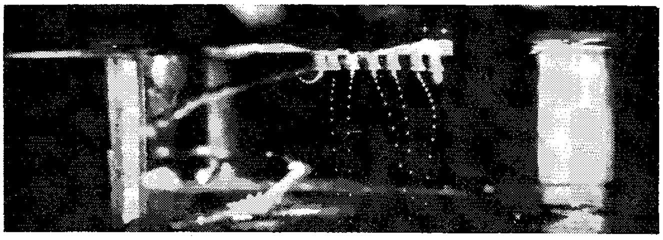


Fig. 7 Stroboscopic photograph of ball falling under gravity and magnetic field at about "$\frac{1}{3}$ g" acceleration.

design a configuration with the maximum volume of uniform acceleration.

A $\frac{1}{8}$-in. steel sphere, the magnetized element, was dropped in the field. The sphere was held at the desired position in the coil by a small flared tube that was connected at the far end to a vacuum (see Fig. 4). In operation the flared tube was moved to the desired position and a steel ball was inserted against the vacuum. A stroboscopic light (set for 80 flashes/sec) was turned on, the coil current was turned on, and then the ball was dropped. Figure 5 shows the ball falling under gravity at three radial positions (the photograph is a triple exposure). Note that six dots occur under each flared tube position. At the lowest position the balls have a velocity of about 2.2 fps so that aerodynamic forces are negligibly small. Figure 6 shows a similar photograph with 20 amp in each magnetizing coil and 6 amp in each gradient coil. Here eight dots are visible, indicating that the vertical acceleration is somewhat reduced. Note that the outer two positions on either side of the center are fairly straight. The extra dots near the bottom are caused by bouncing from the bottom of the coils. Since the acceleration is proportional to the reciprocal of the square of the number of dots (to a first approximation), the relative gravity between Figs. 5 and 6 has been reduced to $\frac{36}{64} = 0.56\ g$.

Figure 7 (22-amp current per magnetizing coil and 8 amp of current per gradient coil) corresponds to about 0.3-g. acceleration. Here the nonuniformities in the present coils dominate the motion of the magnetized balls. These results suggest that care will be required for a system with a large useful volume, particularly for very small or very large accelerations in comparison to the earth's gravity acceleration. However, the field surveys in the larger magnets designed for magnetic suspension systems (see bibliography) show that the desired uniformity can be obtained.

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† The author would like to acknowledge one of the reviewers for calling his attention to Refs. 2 and 3.

‡ The author suspects that many unpublished studies have been made for this problem. In addition to work at MIT, which L. H. Schindel and the present author completed in November 1955, the author is aware of work carried out at the Sandia Corp. by W. Curry. Similarly, studies of this kind were undoubtedly made elsewhere.

Bibliographical Remarks

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Sandahl, C. S. and Faget, M. A., "Similitude relations for free model wind-tunnel studies of store-dropping problems," NACA TN 3907 (1957). The procedure developed in this report is based upon the idea of scaling the trajectory, an approach similar to that already presented. The discussion of the trajectory errors that result from improper scaling is very good. This report also discusses some of the practical problems that are encountered in model constructions.

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The problem of dynamic scaling is mentioned briefly in vonDoenhoff, A. E., "High speed problems of aircraft and experimental methods," *High Speed Aerodynamics and Propulsion VIII*, Pt. D-9, 440–441. The similarity described in Ref. 1 is based upon the Froude number which implies the same gravity scale developed herein.