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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed six manuscript pages and three figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Sabot Opening Lift Force: Analysis, Computation, and Test

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Nomenclature

A_{ref} = reference area ($\pi d^2/4$), in.^{2}
$a, b, \ldots, j$ = sabot surface area segments
C_D = drag coefficient, drag force/($0.5\rho_\infty V_\infty^2 A_{ref}$)
C_M = pitching moment coefficient, pitching moment/($q_\infty A_{ref} d$)
C_N = normal force coefficient, normal force/($q_\infty A_{ref}$)
D = drag force, lbf
d = sabot (and also projectile) reference diameter, in.
L = lift force, lbf
M = Mach number of the flow/projectile
P = static pressure, psi
q = dynamic pressure, $0.5\rho V^2$, psi
u, v = velocity components along axial and radial directions, respectively, ft/s
V = projectile velocity, $\sqrt{(u^2 + v^2)}$, ft/s
α = projectile angle of attack, deg
γ = ratio of specific heats for air, 1.4
Δ_i = flow deflection angle (or surface inclination), deg
ρ = air density, slug/ft^3
∞ = subscript denoting free-stream conditions

Introduction

SABOTS are space adapters used between the subcaliber projectiles and the full-caliber gun tube from which they are launched. They are designed to discard shortly after exiting the tube, hopefully, with minimum effect on the projectiles from which they are discarding. Sabots are usually made in three radially symmetric pieces (sometimes four or two pieces). Sabots are designed to lift away from the projectile body by aerodynamic forces as fast as possible so as not to cause reduction in the velocity of the projectile inside it. Sabots may have one or two forward-facing cup-type hollow cavities designed to generate a lifting force to push the sabot pieces (petals) away from the projectile body. Not many aerodynamic tests have been made on real sabot configurations to measure the actual lifting forces. Some wind-tunnel tests[1] were conducted to provide validation for computational models. These tests provided the pressure distribution on geometrically simplified sabot petals fixed away from the projectile body. In the 1970s, some computer codes[2,3] were developed to simulate the expected sabot discard trajectories using basic aerodynamic analyses to estimate the forces and sabot–projectile interference parameters. In Refs. 2 and 3 the shock expansion method, as well as the simple Newtonian theory, is used to estimate the forces on the simplified sabot geometry. Nevertheless, sabot designs are more focused on minimizing sabot weight based on launch stresses, rather than on attaining a certain aerodynamic lifting force value. In fact, the aerodynamic lifting forces are seldom, if ever, computed.

Computational efforts have also been made[4–6] for idealized sabot configurations. Quasi-steady simulations are made for the same sabot at different locations and angles to the projectile body. Closed sabots are seldom computed because they usually start opening up quickly at 7–10 ft from the muzzle.

The present effort stemmed from the need to estimate the front bourrelet lifting force, so that a steel retaining ring placed around the front portion of the sabot model 1, shown in Fig. 1, could be designed to prevent its opening. Later, computational results were performed. In the present work, an effort to estimate the aerodynamic lifting force of the front cup is presented using the modified Newtonian theory. The aim is to provide a fast engineering estimate for the lifting force of a closed sabot configuration. The computational fluid dynamics (CFD) results give more detailed information about the normal force on the total sabot petal and indicate that the modified Newtonian theory highly overpredicts the normal force value.

Analysis: Modified Newtonian Method

A fast predictive method was sought to provide a first-order value for the lift force generated by the front bourrelet of sabot model 1. This first-order estimate could, and was, used to guide the design of the ring needed to prevent the front end of the sabot from opening.

The modified Newtonian formula,[7] introduced by Lee,[8] is used to provide the lift force estimate. The Newtonian theory (for $M_\infty \to \infty$ and $\gamma \to 1.0$) usually overpredicts the aerodynamic forces and can be considered as an upper bound. The modified Newtonian formula corrects the result for both lower Mach numbers and values of γ

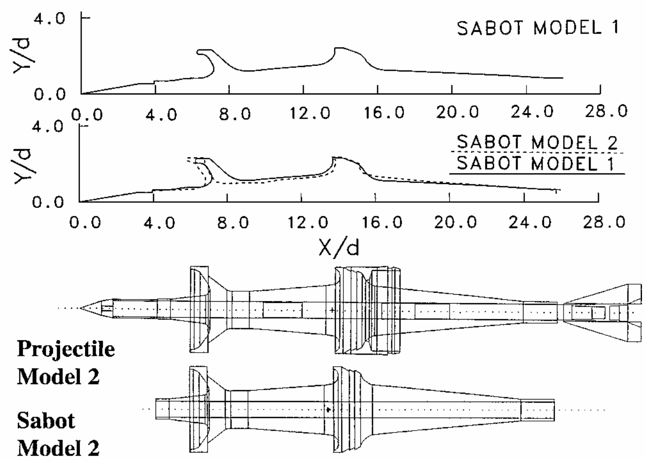

Fig. 1 Geometry of petals of sabot models 1 and 2.

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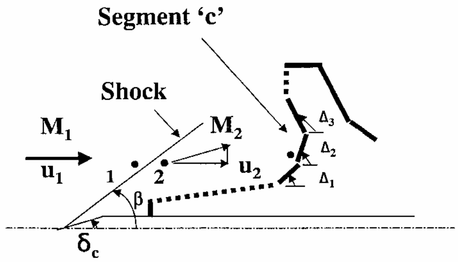

Fig. 2 Schematic for the force analysis for the modified Newtonian method.

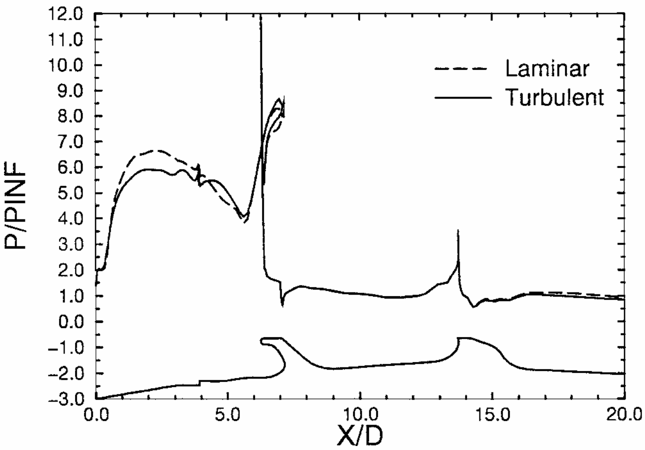

Fig. 3 Surface pressure for sabot model 1, $M = 4.5$.

greater than 1.0. The modified Newtonian formula is simply written as[7]

$$C_p \equiv \frac{P - P_\infty}{0.5\rho_\infty V_\infty^2} = C_{p0} \sin^2(\Delta) \qquad (1)$$

where $C_{p0} = 1.8$ for $M_\infty = 4.5$, $\gamma = 1.4$, and Δ is the angle between the flow stream and the body surface, as shown in Fig. 2.

First, the shock angle for the front cone is computed[9,10] and the shock relations[10] are used to provide the M_2 and ρ_2 at point 2 behind the shock. Next, the surface angles Δ_i are determined for each surface segment. The pressure $(P_i - P_\infty)$ on each segment i is then computed as

$$(P_i - P_\infty) = \frac{1.8 \sin^2(\Delta_i)}{\left(0.5\rho_2 u_2^2\right)} \qquad (2)$$

where P_∞ in this equation refers to conditions at point 2. This computed pressure is then integrated on the surface segments of the front bourrelet. As for the linearized supersonic theorem, the Newtonian theorem does not account or include upstream flow effects.

CFD Computations

The ZNSFLOW[11] code was used to determine the steady-state flow solution. This code is an improved version (optimized and parallelized) of the common F3D code, cited in Ref. 11. The ZNSFLOW code simulates the axisymmetric formulation with only three planes in the azimuthal direction. This code was used routinely in the past with good results for several other similar projectile configurations. Two recent publications[11,12] present examples of the prior use of this code, where it was repeatedly compared with experimental results and validated for those cases.

Two cases were computed, both at Mach = 4.5 and $\alpha = 0$ deg. The first case was to simulate a fully turbulent flow, whereas the second was to simulate the corresponding fully laminar flow case. The results used here are for the fully turbulent flow case.

Figure 3 shows the pressure distribution along the body, with the high surface pressure in the front-circulating flow region and the high-pressure point at the tip of the upper ring of the front cup (represented by the pressure spike at that location). Figure 4 identifies each surface segment of the sabot petal for which results are presented later.

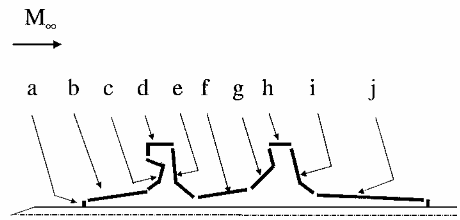

Fig. 4 Sabot surface segments.

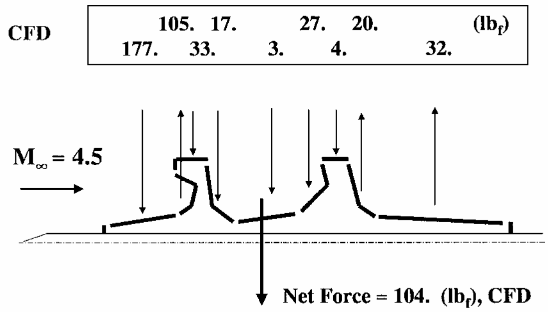

Fig. 5 Normal force on sabot model 1: one petal, $M = 4.5$.

Test

The firing test was performed for four projectiles of model 1 at Aberdeen Proving Ground, Maryland, in October 1998. The first two projectiles had steel restraining rings epoxyed to the sabot by a high-shear-strength epoxy (4500 psi), which had to be cured for 2 days. The other two rounds had six screws drilled in the restraining ring and the sabot to prevent the ring from sliding over the sabot front end. The screws were used as an alternate to the epoxy in case the epoxy design failed to restrain the sabot.

All four projectiles were fired at a speed of 5184 ft/s (1580 m/s), or Mach 4.66. Smear photographs were taken at 49.2 ft (15 m) and 68.9 ft (21 m) from the muzzle, and three yaw cards were placed at 164, 246, and 328 ft (50, 75, and 100 m), respectively, from the muzzle. The photographs showed that the rings, designed based on this estimated lift force, did overcome the estimated lifting force and successfully prevented the sabot from opening up to about 98 ft (30 m) from the muzzle. However, it was then seen that the rear opturator ring had started to discard allowing the sabot rear end to lift off slightly from the rod, allowing air to get between and under the large surface area of the sabot petals and, thus, causing the rear end to lift more. This action caused the sabot to break just behind the restraining ring, during the travel along the 98–164 ft (30–50 m) distance. The cardboard yaw card at 164 ft (50 m) showed the impact of such discard, where the three petals were only a few inches away from the rod hole itself. The same performance was repeated in all of the four projectiles.

Results

The analysis was first performed for sabot model 1. The normal force was computed, using the modified Newtonian, for the surface segment c, and the normal force value was 269 lbf for that segment. The CFD-computed normal force for the same segment was only 105 lbf, indicating that the modified Newtonian theory overpredicts the value by a factor of 1.6. This result is not surprising, because the Newtonian theory is known to provide an upper bound for the pressure. The CFD-computed normal force on all other sabot surface segments is given in Fig. 5. It was highly surprising to observe that the total force on this sabot is pointed downward. One usually expects that the front bourrelet will generate enough normal force to cause an overall upward normal force. The total normal force coefficient for one sabot petal, C_N, is -0.764 (referenced to the rod diameter). The negative sign is to indicate the downward direction.

Because the opening force computed was downward, the drag force on the sabot must be considered if the sabot is to pitch up about its c.g. The drag force and the resultant normal force location were computed using the CFD values and are shown in Fig. 6. Another point was that the location of the resultant normal force was forward of the c.g. location of the sabot; thus, its moment would tend to resist

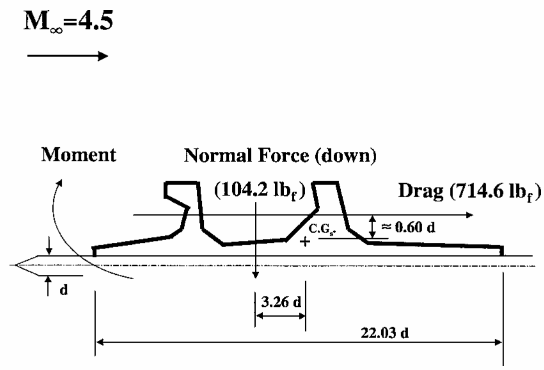

Fig. 6 Pitching-plane forces and moment for sabot model 1: one petal, $M = 4.5$.

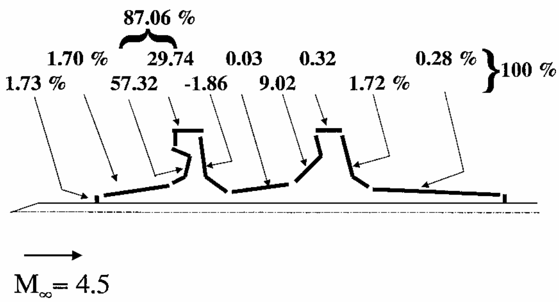

Fig. 7 Drag force components of sabot model 1, $M = 4.5$.

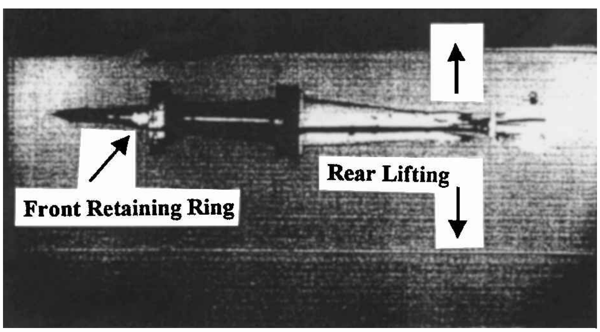

Fig. 8 Smear photograph for projectile-sabot model 1: $M = 4.5$, 21 m from muzzle.

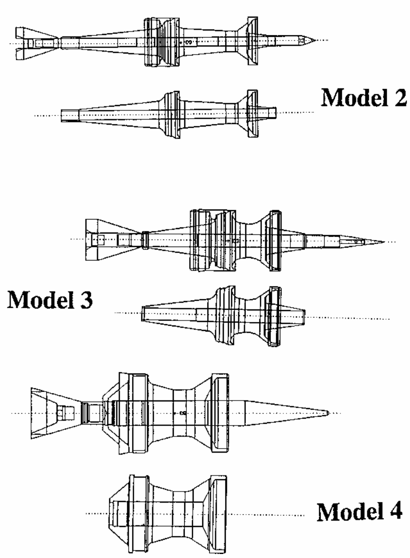

Fig. 9 Sabot-projectile models 2, 3, and 4.

Table 1 Drag anatomy for sabot model 1[a]

Petal surface element	C_D based on rod diameter	Percent of total drag, %
a	0.0384	1.73
b	0.0377	1.70
c	1.2714	57.32
d	0.6597	29.74
e	−0.0413	−1.86
f	0.0006	0.03
g	0.2001	9.02
h	0.0070	0.32
i	0.0382	1.73
j	0.0061	0.28
Total	2.2179	100.00

[a]Mach = 4.5.

Table 2 Sabot models and the modified Newtonian lift force estimate

Sabot model number	Caliber (mm)/ number of petals	Projectile designation	Front bourrelet lift force, lbf
1	120/3	Model 1	269
2	120/3	M829A1	511
3	120/4	M829	236
4	120/3	M865S-TP	650
5	105/3	M833	296
6	105/3	M735	359
7	120/3	Model 7	168

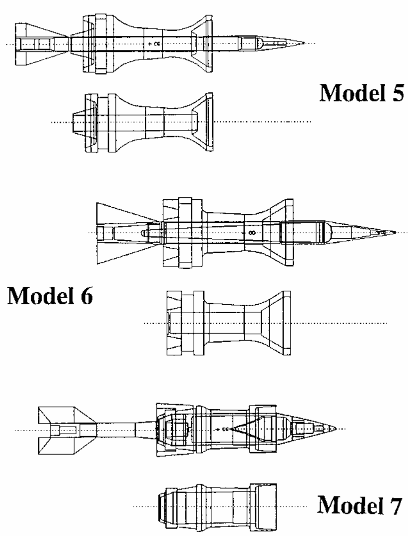

Fig. 10 Sabot-projectile models 5, 6, and 7.

the sabot pitching-up movement. However, the drag force was about seven times the value of the lift force, resulting in a net pitching-up moment about the sabot c.g. The drag component on each surface segment was computed using the CFD results and is shown in Fig. 7. The overall drag coefficient for one sabot petal was 2.218, referenced to the projectile A_{ref}. The drag values are listed in Table 1, and they include the very small viscous drag component. In Table 1, the negative value for surface segment e reflects a local pressure greater than the freestream value, acting in a direction opposite to the freestream flow direction.

Based on these results, it is easier to explain the firing test results. The estimated front bourrelet normal force, obtained from the analysis and used to estimate the restraining ring thickness and material, provided what was later realized to be a highly conservative value for the force. The ring sustained the lifting force and prevented the front end of the sabots from opening for all of the four-fired projectiles, as shown in the smear photograph of Fig. 8. The photograph also shows the rear end of the sabot starting to open. This tail lift-up was unexpected.

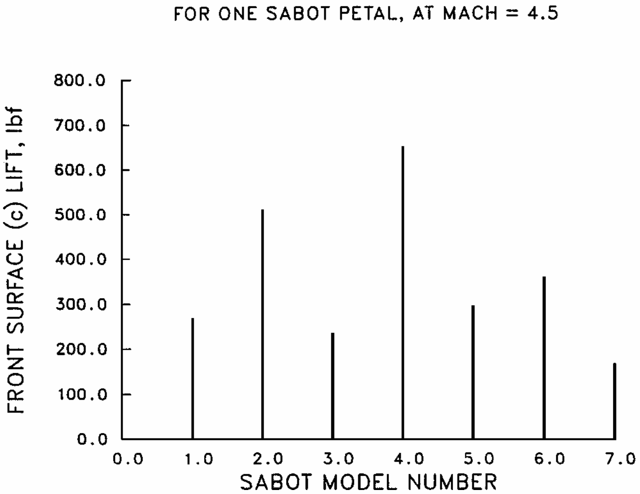

Fig. 11 Comparative front bourrelet normal force results for sabot models 1–7.

The analysis, being overpredictive but simple and fast, was then applied to six other sabot models, as given in Figs. 9 and 10, to examine their relative lifting capability. These sabot models and dimensions were generated by the PRODAS code.[13] These sabots are for both the 120- and 105-mm calibers, as provided in Table 2. Note that sabot model 3 has four petals instead of the more common three-petal design. All calculations were made at Mach 4.5 and the same conditions. The resulting front bourrelet normal force on each petal model is shown in Fig. 11. Sabot models and their corresponding normal forces are provided in Table 2. These predicted forces are to be considered overestimated, possibly by a factor of about 1.6 (based on the CFD results for model 1). An actual test is recommended to be made to provide a validity for the CFD results as well. Meanwhile, the comparative results for the different sabot configurations provide some insight about the relative effectiveness of different front bourrelet designs in producing lift.

Conclusions

Aerodynamic lifting force on a closed, three-petal sabot configuration mounted on its host projectile is analyzed. The modified Newtonian theorem was used to estimate a first-order value for the lifting force on the front bourrelet (during flight in close proximity of the muzzle). CFD calculations were made, and the result suggests that the estimate obtained by the Newtonian method overpredicted the CFD value by a factor of 1.6. The present investigation provides new insight about the aerodynamic forces on the sabot, their relative magnitudes, and the role of the drag force in the sabot opening motion. The modified Newtonian method is applied to a multitude of different sabot models for 120 and 105 mm calibers, to provide comparative values for the front bourrelet lifting force.

The following conclusions are supported by the results obtained for the two-bourrelet, three-petal closed sabot configuration mounted on its host projectile. The conclusions apply to a completely closed sabot, which occurs only during the first few meters from the muzzle. First, the front bourrelet generates a lifting force (upward), but the total normal force on the petal may still be downward. Second, the drag force on the sabot petal studied was about seven times the value of the net normal force, for the configuration considered. Third, the drag force on a petal is a major contributor to the lifting up of the sabot front end, in the initial opening stage. Fourth, anatomy of the drag on the sabot is given, indicating that the front cup contributed 87% of the total drag, whereas the second contributed 11%. Note that the outer ring of the front cup contributes 30% of the total sabot drag. Fifth, the modified Newtonian theorem overestimated the CFD value by a factor of about 1.6 for the current sabot configuration at Mach 4.5. Use of such a method must be accompanied with that realization.

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Atmospheric Reentry Modeling and Simulation

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Introduction

ATMOSPHERIC reentry presents challenges in several domains of engineering and science, being one of the principal research fields in space technology. To provide an environment to design control laws for reentry vehicles, Delft University of Technology (TuDelft) is developing a simulation tool for atmospheric reentry. The simulation tool is called general simulator for atmospheric reentry dynamics (GESARED) and was implemented in MATLAB®/SIMULINK. The simulation tool is meant to work on a personal computer. GESARED was initially developed to be the

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