9-1989

Aerodynamic Forces on Flight Crew Helmets

Timothy A. Sestak
Embry-Riddle Aeronautical University, sestakt@erau.edu

Richard M. Howard
Naval Postgraduate School

Chester A. Heard
Naval Postgraduate School

Scholarly Commons Citation

Sestak, T. A., Howard, R. M., & Heard, C. A. (1989). Aerodynamic Forces on Flight Crew Helmets. *Journal of Aircraft, 26*(9). https://doi.org/10.2514/3.45850

88-2525-CP

A88-40715

AERODYNAMIC FORCES ON FLIGHT CREW HELMETS

Timothy A. Sestak*
Naval Air Development Center, Warminster, Pennsylvania

Richard M. Howard** and Chester A. Heard***
Naval Postgraduate School, Monterey, California

Abstract

Wind tunnel tests were conducted to determine the aerodynamic forces generated on aircrew flight helmets. Three helmets were tested: two used by aircrews flying ejection seat aircraft in the U.S. military, the Navy HGU-33/P and the Air Force HGU-53/P; and one prototype helmet of significantly different shape and volume. Axial and normal forces were measured through a range of pitch and yaw angles. It was found that large forces exist tending to promote helmet loss during ejection, and that simple modifications to the current helmet configurations can reduce those forces by as much as 40%. It is demonstrated that the proper design of future helmet external geometry can contribute to the increased safety and survivability of aircrews in the ejection environment.

Nomenclature

A	= helmet reference area = $\pi(d/2)^2$
d	= helmet reference diameter
C_A	= axial force coefficient = $F_A/(qA)$
C_N	= normal force coefficient = $F_N/(qA)$
C_R	= resultant force coefficient = $F_R/(qA)$
F_A	= axial force
F_N	= normal force
F_R	= resultant force = $[F_A^2 + F_N^2]^{1/2}$
q	= wind tunnel dynamic pressure = $1/2\rho V^2$
V	= wind tunnel velocity
Re	= Reynolds number = Vd/ν
α	= angle of attack
ν	= kinematic viscosity
ρ	= density

Introduction

In the last decade, loss of the flight helmet during ejection from Naval aircraft occurred in approximately 15% to 25% of ejections.[1] Head and neck injuries were incurred by the flight crewman in virtually all cases of helmet loss.[2]

*Director, Vertical Flight Program Office. LCDR U.S. Navy.
**Assistant Professor, Department of Aeronautics and Astronautics. Member AIAA.
***Military Instructor, Department of Aeronautics and Astronautics. LCDR U.S. Navy.

Factors involving aircraft speed and motion, body position, and actuation method of the ejection seat are assumed to have an effect on helmet retention. Air Force studies of limb dislodgment forces during ejection noted that loss of the helmet is common and that lift forces generated on the flight helmet can reach 460 pounds at a speed of 600 knots.[3] Other Air Force studies demonstrated that forces up to 900 pounds can exist at transonic speeds and that helmet loss is inevitable under these conditions.[4]

The injury mechanisms due to loss of the flight helmet were divided into three categories. Wind exposure injuries include damage to soft tissue that occur due to inflation and rupture of tissue such as nasal passages and cheeks; flail and induced vibration injuries of soft tissue and ears; freezing and thermal damage to exposed tissue; and pressure related damage, such as ruptured eardrums and eye injury. Unrestrained motion injuries include head or neck injuries caused by rapid displacement of the head and possible abrupt deceleration due to impact or reaching the limits of normal neck motion. Direct force application injuries include injuries due to tensile extension of the neck and abrasion and contusion injuries caused by violent helmet removal.

If the helmet does not greatly increase the forces causing unrestrained motion, its presence for protective functions in absorbing impact and preventing wind exposure would reduce the severity of ejection related injuries. Reducing the magnitude of helmet-induced aerodynamic forces should work to restore one function of the aircrew flight helmet -- protection in the ejection environment.

Test Facility and Models

Wind Tunnel

Experimental tests were performed in the 3.5- by 5-foot wind tunnel at the Naval Postgraduate School. This tunnel has a turbulence intensity of 1.2% at the test velocity; not a low value. All helmets were tested at the same dynamic pressure which, with the application of a blockage correction,[5] resulted in a test section velocity of 214 ft/s or 127 kts. The front to back helmet diameters varied from 10.5 inches to 12.5 inches, giving a Reynolds number of approximately 1.2×10^6. The turbulence intensity results in a turbulence factor[5] of 1.95 and an effective Reynolds number of 2.34×10^6 for the flight helmets. The definition of an effective Reynolds number only has application where turbulence intensity, and not turbulence scale, comes into play; such is the case for spherical bluff bodies, where the important mechanism is whether the flow separates in the laminar or turbulent state. This transition mechanism is dependent upon small-scale turbulence, but is relatively insensitive to the exact turbulence scale over an order of magnitude of values.[6]

An anthropomorphically correct headform was used to mount each helmet and oxygen mask assembly. A six-component strain-gage balance was mounted in the headform to measure the loads on the helmet/headform unit. A cradle and sting arrangement allowed the headform to rotate about the pitch and yaw axes. A strip of soft expanded plastic foam filled the gap between the neck of the headform and the cradle to prevent airflow through the gap. The cradle assembly covered the bottom of the headform to prevent the transmission of dynamic pressure to the bottom of the headform neck. Any interference effect of the supporting mechanism would be the same for all models. The Navy helmet in the wind tunnel is shown in Fig. 1.

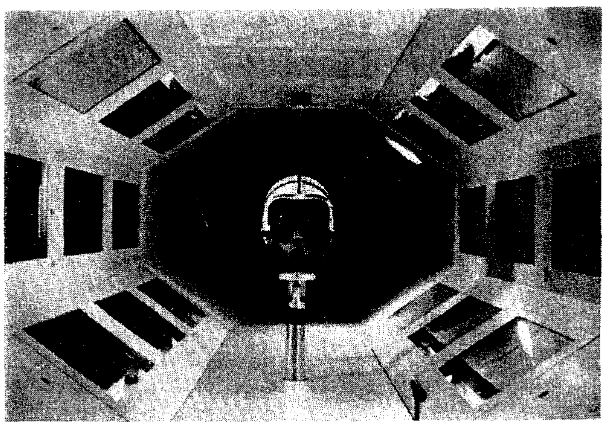


Fig. 1 Navy helmet mounted in wind tunnel.

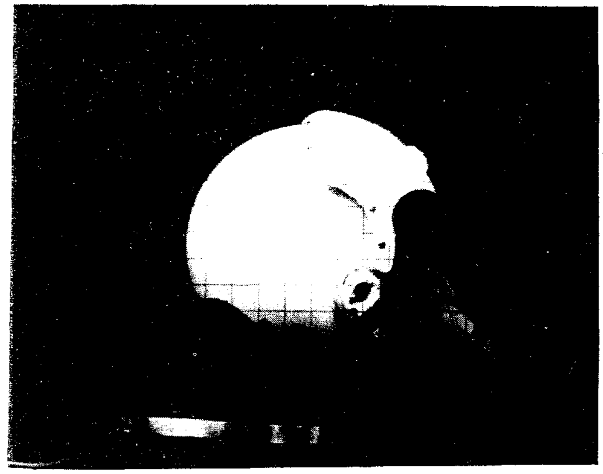


Fig. 2 Navy helmet installed on cradle/headform assembly.

Fig. 3 Air Force helmet installed on cradle/headform assembly.

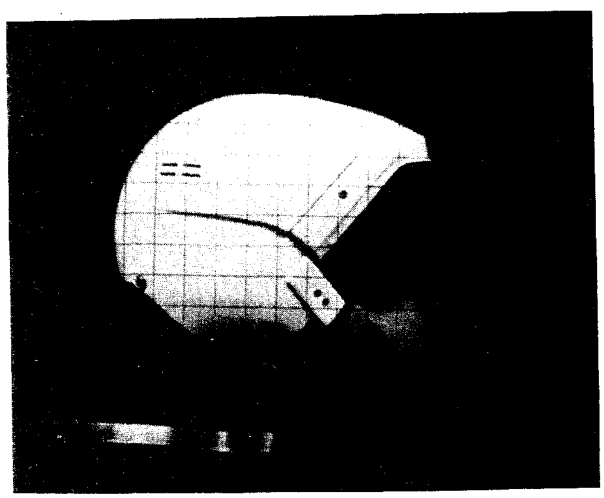


Fig. 4 Prototype helmet installed on cradle/headform assembly.

Helmets

The helmets used in the study were the U. S. Navy HGU-33/P, the U. S. Air Force HGU-53/P, and a prototype helmet. The prototype was designed to contain within its volume the equipment necessary to project visual information on the inside of a parabolic visor. The three helmets are shown in Figs. 2-4.

Force coefficients have been made dimensionless using the reference area of the Navy helmet, taken at the maximum diameter in the horizontal plane. A common reference area was used in order to relate the actual forces the pilot will experience (by comparison). The equatorial areas of the helmets are: Navy, 0.573 $ft.^2$; Air Force, 0.562 $ft.^2$; and prototype, 0.701 $ft.^2$.

Each helmet was attached to the headform with the helmet straps and additional bolts in the back of the helmet. The oxygen mask assembly was mounted with each helmet, but the hoses to the masks on the Navy and Air Force helmets presented a hazard in the wind tunnel and were removed for the purposes of this study.

Modifications

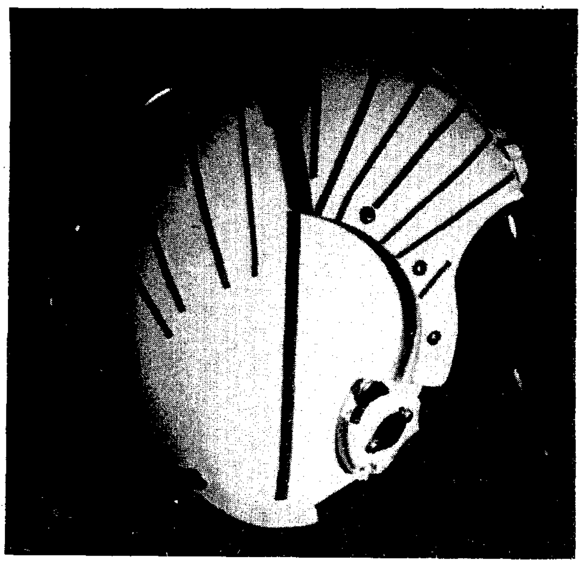
Modifications of the helmets were devised under the assumption that a reduction of the aerodynamic forces on the helmet would decrease the likelihood of helmet loss and subsequent injury. The pertinent choice was the axial force (extending from the spine); the head and neck have limited motion in the axial direction, and axial forces would tend to remove the helmet rather than move the head. No gross structural changes were planned for the helmets currently in use; the modifications consisted of easily implemented additions to the external surface. The prototype helmet was modified in shape with the use of modeling clay.

Four modifications to the Navy helmet were tested. For ease of discussion, the modifications will be referred to as mod 1, mod 2, etc. Navy mod 1 involved increasing the roughness of the helmet surface with reflective tape already commonly in use on flight helmets. A dozen 1/4-inch wide strips of 0.008-inch thick tape were placed over the top surface of the helmet in equatorial fashion, as shown in Fig. 5a.

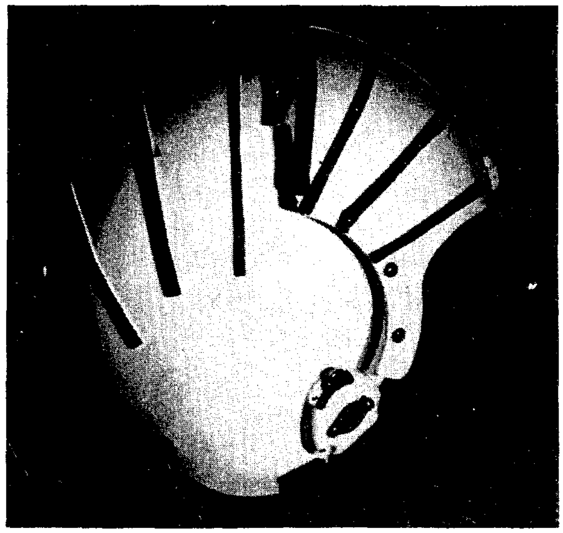
Navy mod 2 involved a similar placement of material on the helmet, but with 3/16-inch thick strips of dense foam of 1/4-inch widths and spaced at intervals of 1.5 inches. Navy mod 2 is shown in Fig. 5b.

Navy mod 3 used three strips of 3/16-inch thick expanded foam weather stripping, 3/8-inch in width, hereafter referred to as soft foam strips. The strips were placed at the lateral mid-line of the visor cover, at the top edge of the visor cover, and at a location 3 inches aft of the visor cover. The Navy helmet with mod 3 is shown in Fig. 5c.

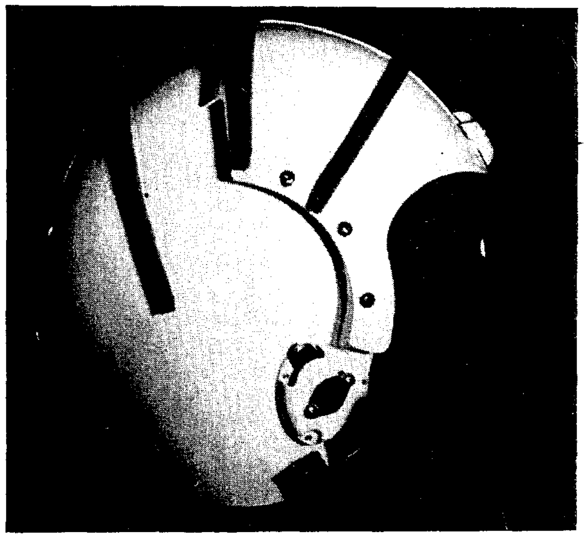
Navy mod 4 involved the further addition of soft foam strips to mod 3. One piece was added on each side from the edge of the visor cover across each ear cup to the bottom edge of the helmet; two pieces were added across the front leading edge of the visor cover. Navy mod 4 is shown in Fig. 5d.



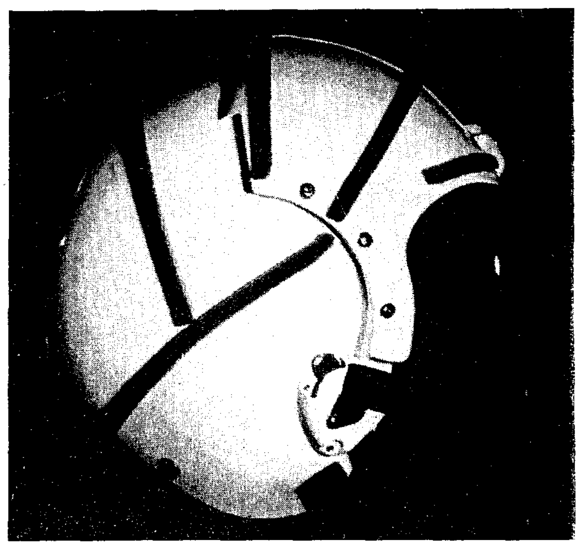
a) Navy mod 1



b) Navy mod 2



c) Navy mod 3



d) Navy mod 4

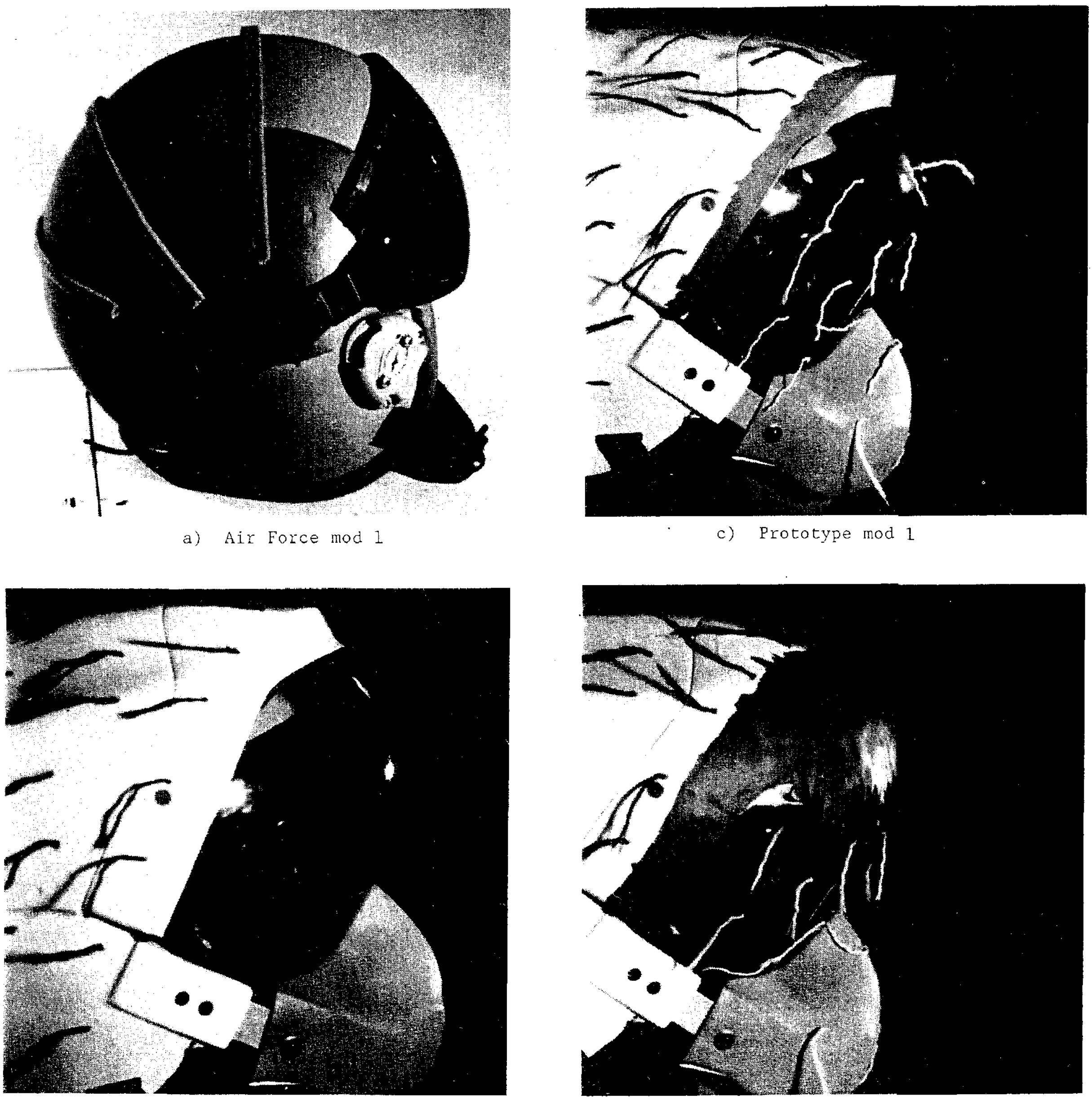
Fig. 5 Navy helmet modifications.

A single modification of the Air Force helmet was examined. The Air Force mod consisted of the addition of three soft foam strips similar to mod 3 of the Navy helmet, as shown in Fig. 6a. The modifications to the prototype helmet were primarily changes in the external geometry with the use of modeling clay. The prototype helmet is significantly different from the other helmets in shape, having a broad flat top and a parabolic visor with an insectlike appearance. Gross geometry changes were felt warranted in the case of the prototype helmet. Original prototype geometry was partly due to an effort to reduce aerodynamic forces generated on the helmet during ejection. The effect of each modification to the prototype shape was noted, and this information was used in subsequent modifications in an effort to further reduce the aerodynamic forces.

Prototype mods 1 and 2 were attempts to extend forward the step above the visor to create a bluff "stall fence" effect. The step was moved forward to a vertical position in mod 2 and to a position 10 degrees forward of vertical in mod 1, referencing the eyes level, zero pitch position. The prototype baseline and mod 1 are shown in Figs. 6b and 6c. Tufts are attached to the helmet for flow visualization.

Prototype mod 3 involved the addition of two soft foam strips to mod 2, across the top of the helmet, 3 inches apart and 3 inches aft of the helmet step.

Prototype mod 4 eliminated the step completely by a smooth faring of the visor curve into the top of the helmet. This mod is shown in Fig. 6d.



a) Air Force mod 1

c) Prototype mod 1

b) Prototype helmet, tufted

d) Prototype mod 4

Fig. 6 Air Force and prototype helmet modifications.

The remaining three modifications involved the addition of crests to the top of the prototype helmet. Mod 5 extended the step vertically 1/4-inch to create a flat horizontal surface on the top of the helmet from the step to the high point of the crown. Prototype mod 6 extended the flat surface to the sides and beyond the crown aft so that the top surface of the helmet was flat at zero degrees pitch. Prototype mod 7 involved the addition of a longitudinal crest along the fore and aft centerline sloping aft throught the high point of the crown and laterally to the shallow side grooves.

Experimental Procedure

The voltage readings from the six balance channels and from the pitch angle potentiometer were sequenced and measured through a signal conditioner, relay multiplexer and digital multimeter. Data were stored and the test controlled with a microcomputer. Pitch angles of the helmet/headform assembly varied from -46 to +32 degrees, with measurements taken at 2-degree intervals. Pitch angles were reproducible to within 0.1 degree.

Results

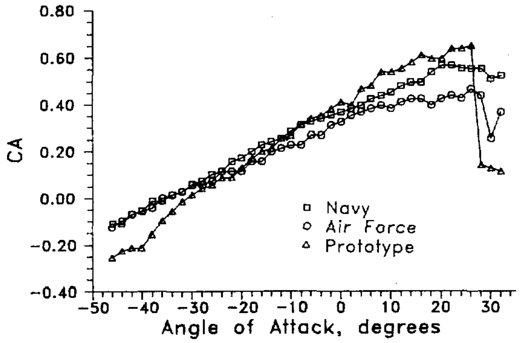
Forces were referenced to the balance coordinate system. A positive axial force represents a tensile force along the spinal direction, and a positive normal force tends to push the head backward. The direction of the resultant force is given relative to the freestream direction.

Baseline Helmet Comparison

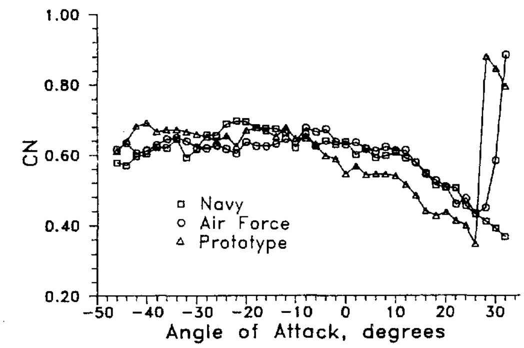
The three unmodified helmets were tested throughout the range of pitch angles and at yaw angles of 10, 25 and 45 degrees. All of the helmets showed distinct aerodynamic characteristics of a lifting body, as opposed to those expected of a spherical shape. Fig. 7a shows the axial force coefficient versus angle of attack.

The helmets can be seen to exhibit zero axial force at pitch angles between -30 and -35 degrees. Conventional stall behavior is indicated by all helmets, but the prototype exhibits distinct differences from the others in two areas. The lift curve slope is much steeper for the prototype; the maximum value of C_A is 25% to 30% higher than that for the Air Force helmet. Secondly, the stall behavior for the prototype is much more adverse than for the others. The Navy helmet shows a gentle stall behavior; the Air Force helmet shows an indication of a stall break at 28 degrees. But the prototype helmet shows a sharp break at 27 degrees to an axial force that is only 20% of its prestalled value.

The normal force coefficient versus angle of attack plot for the unmodified helmets is shown in Fig. 7b. Both the Air Force and the prototype helmets show a strong rise in the normal force at stall as the resultant force vector rotates backward on the helmet. It is possible that such abrupt changes in force direction are responsible for unrestrained motion injuries, and the magnitudes of the forces themselves for



a) Axial force coefficient



b) Normal force coefficient

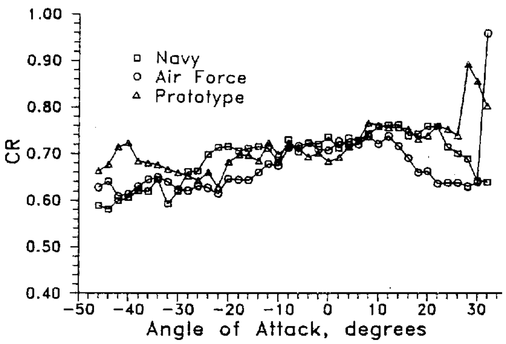
Fig. 7 Comparison of axial and normal forces for baseline helmets.

direct force application injuries and the possible removable of the helmet and subsequent wind exposure injuries.

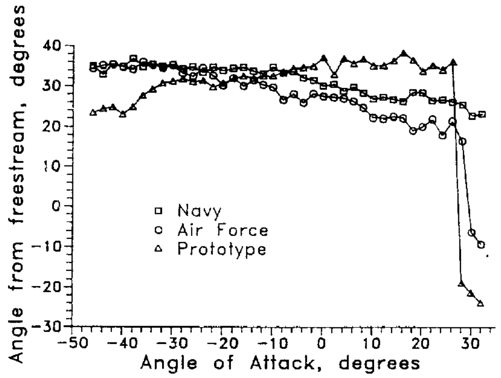
Resultant force data are plotted in Fig. 8. The Air Force and prototype helmets show distinct rises in magnitude at the stall condition. The force vectors can be seen in Fig. 8b to shift in direction from above to below the freestream reference; in particular, the prototype helmet force vector has rotated from 35 degrees above the freestream to a direction 20 degrees below the freestream in a 2-degree increment of angle of attack. Such abrupt changes can only aggravate the helmet loss problem.

A survey of axial forces with varying yaw angle was conducted for each baseline helmet. The changes with yaw were modest, and the case for the Navy helmet is shown in Fig. 9 as a representative example. The noticeable difference between the helmets was that the Navy helmet was the only one to show a decrease in axial force with yaw angle; the other two showed a slight increase. Examination of the external geometry of the helmets revealed that the Air Force and prototype helmets exposed increasing smooth surface area with increasing yaw angle, while the Navy helmet exposed the sharp raised step of the visor housing. This observation was later used in subsequent modification of the helmets.

Due to the distinct behavior of the prototype helmet, a flow visualization study was per-



a) Resultant force coefficient



b) Resultant force direction

Fig. 8 Resultant force magnitude and angle for baseline helmets.

formed using yarn tufts. The photos in Fig. 10 indicate the separated flow phenomena over the complete angle of attack range. Figure 10a shows fully attached flow over the top and side of the helmet at -46 degrees. A small separation region can be seen to have formed over the lower side of the helmet at zero degrees angle of attack in Fig. 10b. Increasing the pitch to 10 degrees (Fig. 10c) brings a separating vortex along the corner region between the side and the top of the helmet; a separation bubble has

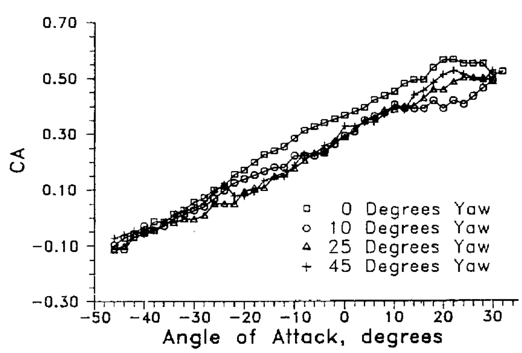
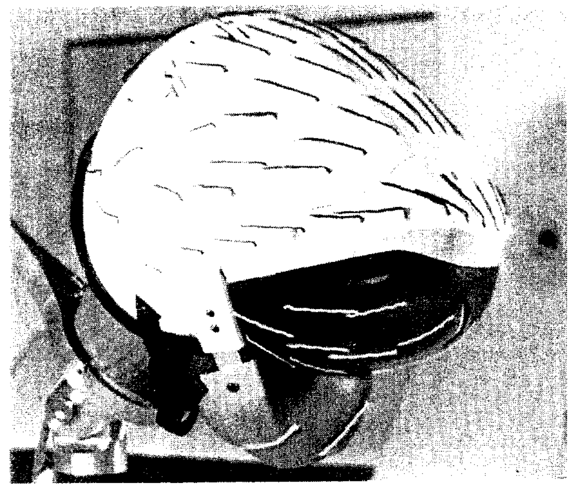
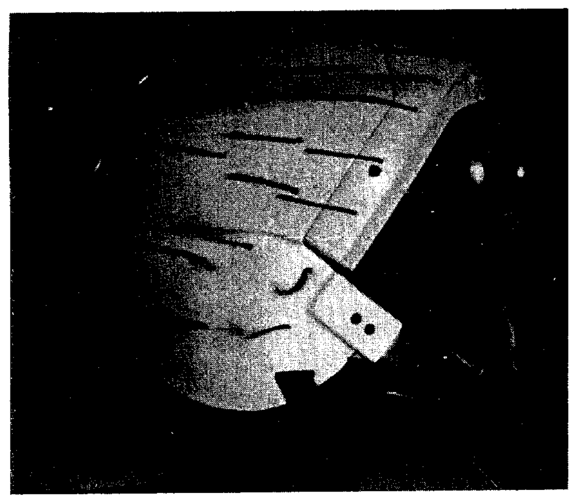


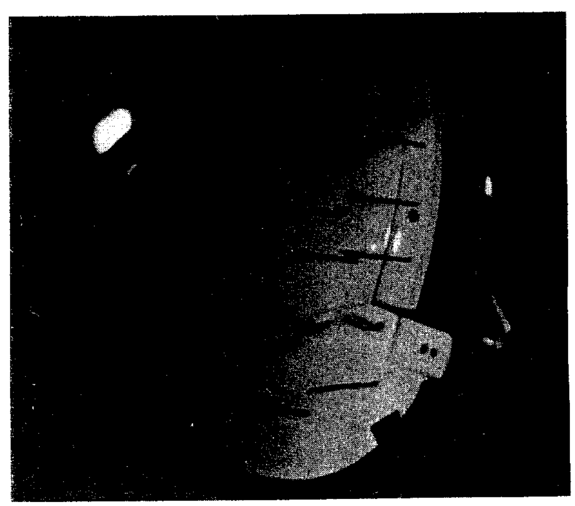
Fig. 9 Navy baseline helmet axial force change with yaw.



a) α = -46°

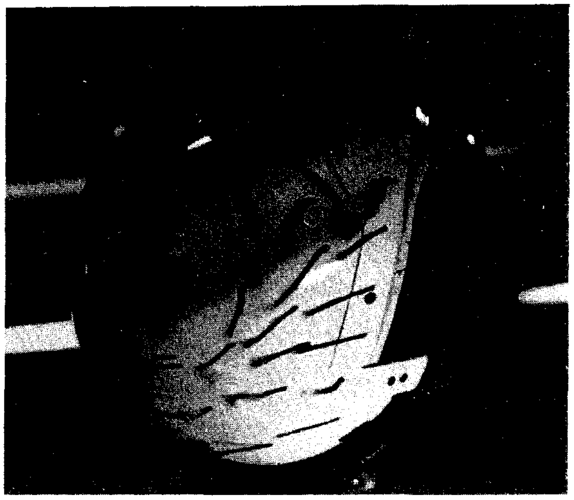


b) α = 0°



c) α = 10°

Fig. 10 Prototype helmet flow visualization.



d) α = 28°

Fig. 10 Prototype helmet flow visualization (cont'd.).

formed at the step above the visor but has reattached over the top of the helmet. Figure 10d shows the flow just after the stall condition; the flow over the top is completely reversed.

Modification Comparison

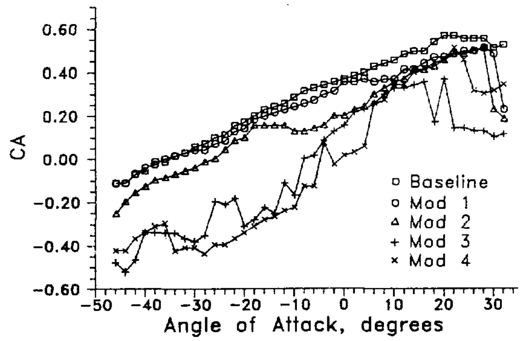
The effects of the modifications to each helmet will be compared to the behavior of the baseline helmet.

Force coefficients for the baseline Navy helmet and its four modifications are shown in Fig. 11. Navy mod 1 resulted in small but consistent reductions in the axial and normal forces, and also reduced the angle from the horizontal at which the resultant force acted. Mod 2 showed a slightly greater reduction in axial force, and a reduction in the resultant force angle of approximately 10 degrees. Mods 3 and 4, consisting of the thicker soft foam, caused substantial reductions in axial force. The onset of positive axial force tending to remove the helmet was delayed over 25 degrees of pitch angle. Mod 4 shows a greater reduction of axial force until a pitch angle of 10 degrees is reached; from this point on, mod 4 results in higher values of axial force.

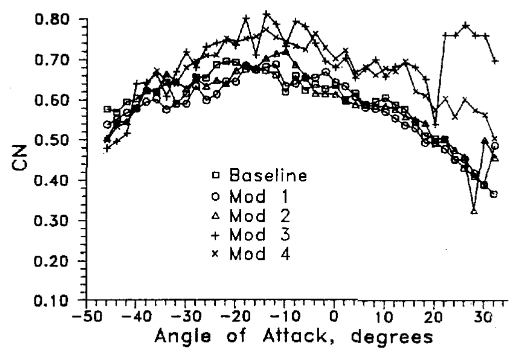
From the normal force coefficient graph in Fig. 11b, the reduction in axial force at high pitch angles of mod 3 is seen to be offset by an increased normal force; the effect is due to the rotation of the force, rather than the reduction of it. This conclusion is confirmed in Fig. 11c, where Mods 3 and 4 produce resultant force directions that vary little from the freestream, therefore not tending to promote helmet loss. Due to its reduced axial component at high pitch angles, Navy mod 3 was considered to be the most successful. The larger foam strips are believed to reduce the resultant force angle by acting as lift "spoilers"; that is, by causing flow separation, reduced lift, and increased drag.

Modifications to the prototype helmet included geometry changes and the addition of foam strips similar to Navy mod 3. Mods 1 and 2 changed the angle of the step above the visor; mod 4 blended the curve of the visor into that of the top surface.

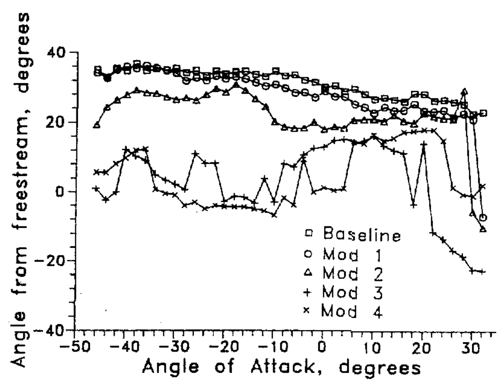
Protoype mods 1 through 4 were basically ineffective. Axial forces were reduced only slightly, and the first three modifications initiated stall less than 10 degrees sooner than the baseline. Mod 4 did not stall within the test pitch angles. Flow visualization studies revealed mods 1 and 2 to cause a leading edge separation bubble with subsequent reattached flow, as shown in Fig. 12 at zero degrees angle of attack. The flow was found to reattach even over the soft foam strips of mod 3. The proto-



a) Axial force coefficient



b) Normal force coefficient



c) Resultant force angle

Fig. 11 Axial and normal forces for Navy helmet modifications.

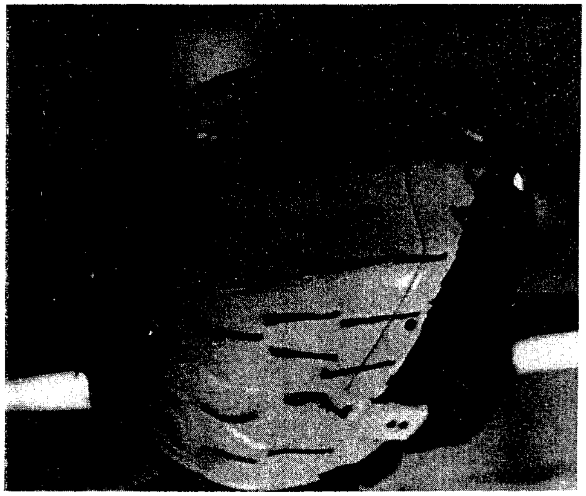
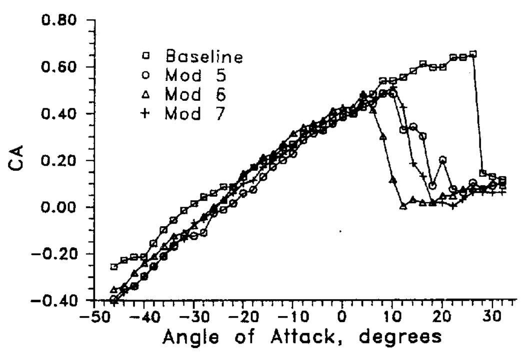


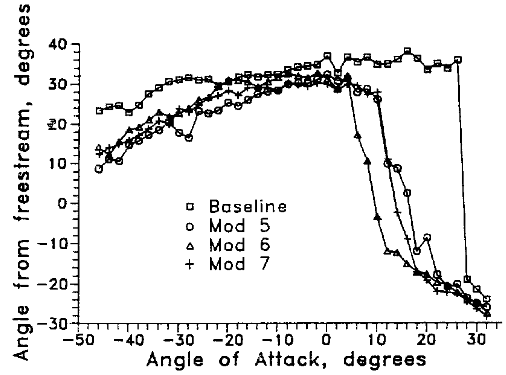
Fig. 12 Flow visualization, prototype mod 2, zero degrees angle of attack.

type helmet simply favors attached flow, promoted by the bulbous visor and the far-aft high point of the helmet, as can be seen in Fig. 4.

Subsequent modifications of the prototype attempted to introduce an adverse pressure gradient over the top of the helmet at lower pitch angles. The results of mods 5, 6 and 7 are compared to the baseline in Fig. 13. Each mod



a) Axial force coefficient

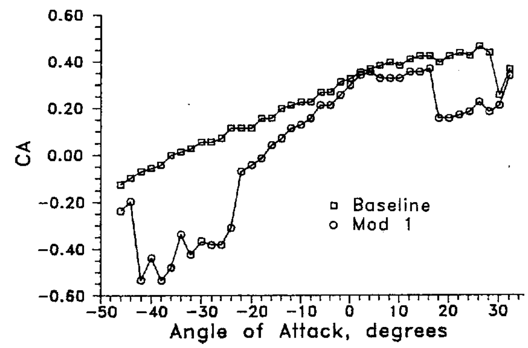


b) Resultant force direction

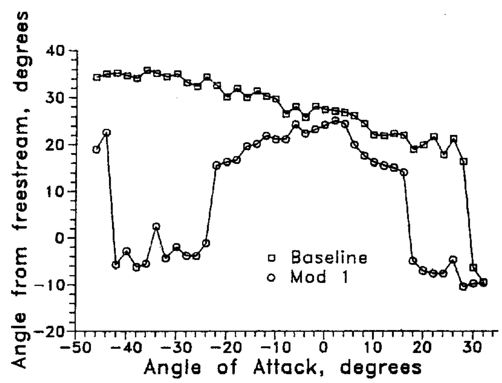
Fig. 13 Comparison of prototype helmet modifications.

showed a small reduction in the axial component as shown in Fig. 13a, but the major difference was the earlier stall angle exhibited. Mod 6 stalled 20 degrees sooner than the baseline configuration, with a post-stall force near zero. The sharp increase in the normal force at stall, caused by the resultant force rotating abruptly downward, can be noted in Fig. 13b. In fact the resultant force vector continued to rotate well below the freestream direction as pitch angles were increased.

A single modification was attempted with the Air Force helmet. The application of soft foam strips which had significant effects on the Navy helmet proved to be somewhat ineffective on the Air Force helmet. As can be seen in Fig. 14, only the values at the extremes of the pitch range showed significant changes. It is evident that a more thorough "tuning" process is required for a complete optimization of helmet modifications.



a) Axial force coefficient



b) Resultant force direction

Fig. 14 Comparison of Air Force helmet modification.

Conclusions

For the helmet and oxygen mask systems tested, geometry was found to play a large part in generating aerodynamic forces. Modest changes in surface configuration were shown to have significant effect on those forces.

The Navy and Air Force systems had similar characteristics, with differences being the maximum force developed and the angle reached at stall. The Air Force helmet generated lower overall aerodynamic forces than the Navy helmet by 5% to 10% at the maximum value. Over the range of pitch angles tested, the Air Force helmet demonstrated a distinct stall behavior marked by an abrupt decrease in axial force and an increase in normal force. In this range of angles, the Navy helmet did not stall.

The prototype helmet exhibited a much more pronounced aerodynamic behavior than the others. The maximum axial force measured was 40% greater than that for the Air Force and 15% greater than that for the Navy helmet. The prototype exhibited a steeper axial force curve and a much more abrupt stall behavior than the other helmets. Until the stall, the normal force was consistently smaller than for the others. As the pitch angle increased, the direction of the resultant force generated by the prototype helmet rotated forward, away from the freestream direction, unlike the motion of the resultant forces for the other two helmets. After stall, the resultant force for the prototype dropped below the freestream direction and below those of the other two helmets. Flow visualization studies showed the particular geometry of the prototype helmet to favor attached flow over the helmet top surface.

The proper placement of 3/16-inch obstructions to the flow on the Navy helmet reduced the axial force by 40%, with an increase in normal force of 15% to 25%. The modification that produced marked changes in the behavior of the Navy helmet had considerably less effect applied to the Air Force helmet.

Attempts to disrupt the flow over the top surface of the prototype helmet failed to prevent reattachment until the shape was significantly altered; large axial forces were maintained despite the addition of flow obstructions. It is expected that significant changes in the external geometry of the prototype would be required to decrease the axial force and to mollify the adverse stall behavior.

The task of improving the conditions for flight crew safety and survivability through aerodynamic tailoring of helmet geometry is not a trivial one. Helmet loss is a likelihood in 40% of the survivable ejections that occur in the 300+ knot speed regime. In an ideal ejection sequence, the simple modification applied to the Navy helmet shows the potential of reducing the upward force that would tend to remove the helmet from the pilot's head by a factor of two. Continued investigation is likely to bring significant rewards.

Just as important as the modification of existing helmet systems is the design of future ones. The demand on helmet design will be driven by the tasks the helmet must serve and the electronic equipment it must carry within its volume. No longer will the flight helmet operate solely as a protection and communication device. Proper use of the required volume in modern flight helmet systems may be able to produce an external helmet geometry considerably more benign in the ejection environment than those currently in use. More research is necessary to determine how the aerodynamics of the flight helmet can be used to reduce the hazards to an aircrewman already in a tenuous survival situation.

References

[1]Helmet Retention of Personnel Ejecting from Navy/Marine Corps Aircraft, Naval Safety Center Statistical Study, Naval Safety Center, Norfolk, Virginia, 1985.

[2]Head/Neck Injuries During Ejection, FSR Management Report No. R0490BA, Naval Safety Center, Aviation Shore Branch, Norfolk, Virginia, 1987.

[3]Payne, P. R., Hawker, F. W., and Euler, A. J., Stability and Limb Dislodgment Force Measurements with the F-105 and ACES-II Ejection Seats, AMRL-TR-75-8, Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio, July 1975.

[4]Newhouse, H. L., Payne, P. R., and Brown, J. P., Wind Tunnel Measurements of Total Force and Extremity Flail Potential Forces on a Crew Member in Close Proximity to a Cockpit, ARML-TR-79-110, Wright-Patterson Air Force Base, Ohio, 1974.

[5]Pope, A., and Rae, W. H. Jr., Low-Speed Wind Tunnel Testing, 2nd Ed., John Wiley and Sons, New York, 1984.

[6]Bearman, P. W., and Morel, T., "Effect of Free Stream Turbulence on the Flow Around Bluff Bodies," Progress in Aerospace Science, Vol. 20, pp.97-123, 1983.