Free-Fall Vehicle Dynamics Observation and Prediction

Frank J. Regan*
U.S. Naval Ordnance Laboratory, Silver Spring, Md.
Frank J. Tanner†
Royal Aircraft Establishment, Farnborough, Hants, England
and
Jonathan H. W. Shannon‡
Weapons Research Establishment, Australia

During the past five years, the U.S. Naval Ordnance Laboratory, the Royal Aircraft Establishment, and the Australian Weapons Research Establishment have been engaged in a joint study of free-fall vehicle dynamics. The goal of this program was to obtain highly detailed wind-tunnel measurements on research shapes and then use these data to carry out computer simulations of vehicle trajectories. These simulations were compared with actual measurements obtained from a full-scale instrumented store in free flight. The program was also concerned with a wind-tunnel and free-flight investigation of novel stabilizers (tails) designed to eliminate various types of dynamic instabilities.

1. Introduction

FOR the past five years, there has been in existence a cooperative bomb-stability program among the Australian Weapons Research Establishment (WRE), the Royal Aircraft Establishment (RAE), and the Naval Ordnance Laboratory (NOL). This current program had its origin in the joint effort between RAE and WRE begun in 1960. The earlier program was initiated as a result of a mutual interest in the development of design criteria for bombs and a recognition of the need for data on the effect of bomb dynamic stability on trajectories.[1] Technical discussions with U. S. research establishments, in particular the Naval Ordnance Laboratory, began in 1963 and since 1964 the work has been pursued as a tripartite cooperative program. Since its initial formulation, the program has had three main aims: 1) to obtain the most complete wind-tunnel and free-flight data possible and, by the use of mathematical models, to coorelate the predicted with observed behavior, and hence provide a check on current stability theory; 2) to investigate, theoretically and experimentally, ideas and techniques which offer solutions to some of the stability problems and possibly greater tactical flexibility in weapon design; 3) to develop where necessary new experimental methods for measuring aerodynamic data.

Initially, the program was based upon a conventional U.K. design for a bomb with low- and high-drag modes. These became known by their U. K. wind-tunnel numbers as the M557A for the low-drag mode and M557B for the high-drag mode. Subsequently, a modification was made to the base of the M557A model in order to remove a nonlinearity in the static pitching moment. The resulting configuration became the basic research shape and was designated as the M823. Except for this afterbody modification, the M823 and M557A are identical. Figure 1 presents the geometry and the essential dimensions of this store. In addition to using the M823 in basic dynamic studies, the effort was extended to include various unconventional stabilizers. The conventional cruciform stabilizer of the M823 was then replaced by such devices as free-spinning cruciform, free-spinning monoplane and split-skirt tails. The free-spinning cruciform tail is achieved by making provision for the cruciform tail to spin about the longitudinal axis of the body. The free-spinning monoplane follows from the free-spinning cruciform by removing two opposing fin panels. The split-skirt stabilizer is a four-petal device illustrated in Fig. 2.

2. Flight Dynamic Problems

Three basic phenomena in flight dynamics were to be investigated by this program.

1) Roll yaw resonance instability, which is predicted by linear theory to arise from the presence of small configurational asymmetries, together with an acceleration in roll which can lead to roll frequencies which resonate with the pitching frequencies. The magnitude of the resulting insulting instability depends upon the rate with which the resonant region is traversed.[2,3]

2) Catastrophic yaw which is exhibited by missiles having low-roll rates and is caused by the roll-attitude-dependent yaw-induced rolling moments and side moments. It is essentially nonlinear in character.

3) Magnus instability which occurs at high roll rates with destabilizing moments which are dependent both on spin rate and yawing amplitude. Evidence suggests that these moments are also highly nonlinear.[4]

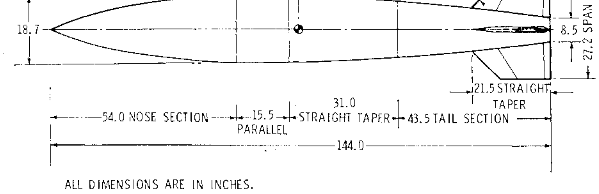

Fig. 1 M823 free-fall research store with cruciform stabilizer.

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* Aerospace Engineer, Applied Aerodynamics Division.
† Senior Experimental Officer, Weapons Department.
‡ Principal Research Scientist, Principal Officer for Free Flight Research Group, Aerodynamics Division.

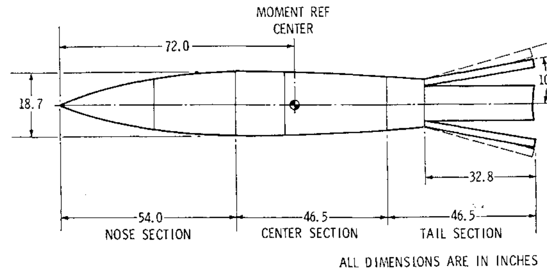

Fig. 2 M823 free-fall research store with split-skirt stabilizer.

3. Flight Trials Technique

In order to make an adequate assessment of the flight characteristics of a free-fall store, it is necessary to have some sort of continuous record of its angular attitude and position throughout the flight. Qualitative judgments based upon rather simple measurements made during the flight would not be adequate. From the onset of the program, it was decided to measure vehicle behavior in three separate ways: First, ground-based cameras would observe the trajectory of the bomb. Secondly, there would be various transducers internal to the bomb to measure quantities such as acceleration and static pressure. The output of these transducers would be telemetered to the ground. Third and finally, various aircraft-mounted cameras would record the disturbance imparted to the bomb at release and its subsequent motion through the near flowfield of the airplane.

The ground instrumentation consisted of Contraves kinetheodolites to determine vehicle trajectory, and high-speed 35-mm motion-picture cameras fitted with long focal length lenses to yield a complete photographic record of the vehicle's behavior during fall.

The internal instrumentation consisted of variable inductance transducers used in conjunction with a 24-channel telemetry system. These enabled accelerations and incidence angles to be sampled at a rate of 80 points per second. Lateral forces and moments were deduced from the readings of six accelerometrrs, one pair placed ahead of the vehicle's center of gravity and two pairs aft. Incidence was measured by two pairs of differential pressure transducers set in the vehicle's nose. Roll rate was deduced from the output of photoelectric cells placed behind two slits in the body surface. The output of these photoelectric cells was also telemetered to the ground.

The aircraft used in the trials, a Canberra B2, carried typical range-type camera instrumentation to cover fully the release and initial response of the vehicles.

It is clearly wasteful to use a bomb dropping program to derive aerodynamic data where only a very small part of the trajectory, that near release, is subject to moderate incidences. It was decided to conduct a number of experiments during some flights by firing lateral pulse rockets to initiate large incidences. The times of firing these "bonkers" were chosen to give information at a series of discrete Mach numbers. True airspeed of the vehicle in flight was obtained from the kinetheodolites, Mach and Reynolds numbers and freestream dynamic pressure required range meteorological measurements in addition. These data, together with the inflight measurements of lateral acceleration, angle of attack and roll rate, enabled complete histories of the total aerodynamic forces to be made. A mathematical model of the force system was then used in a computer program to evaluate particular aerodynamic coefficients.

4. Flight Test Program

Within the context of the program goals, the high-drag M557B shape proved uninteresting. The small yaw-induced forces and moments coupled with only moderate release disturbances resulted in uneventful flights. Thus, after four releases, further work on the bluff-nosed body was halted. Effort was concentrated on the low-drag vehicles both with the conventional cruciform stabilizer and the novel stabilizers that were tested later.

The low-drag vehicles were constructed with ballast weights to enable center-of-gravity position to be set as required by the particular experiment. The fins were accurately made and were capable of being set to any desired fin cant angle up to $3\frac{1}{2}°$. In practice, the center of gravity varied from 47.4 to 57.3% of body length and fin cant angles in the range of 0° to 2.8°. An illustration of a low-drag M823 store prior to final assembly is presented in Fig. 3.

Releases took place at a range of Mach numbers and altitudes but the majority of the tests were performed at Mach numbers of 0.70 to 0.75 from 45,000 ft.

5. Wind-Tunnel Tests

Earlier it was mentioned that one of the major goals of the program was to correlate observed behavior of the bomb with trajectory simulations. These simulations would involve using a six degree-of-freedom digital computer trajectory program.[5] Commensurate with such a detailed mathematical model would be an equally detailed set of wind-tunnel data. For this reason, an elaborate set of wind-tunnel measurements was made on each of the various configurations planned for trials. These tests were carried out in wind tunnels at the Aeronautical Research Laboratories in Australia,[6] at the Aeronautical Research Association,[7] and the Royal Aircraft Establishment tunnels in the U.K. and the Naval Ship Research and Development Center and the Naval Ordnance Laboratory, White Oak in the U.S.[9,8] In the ARL and RAE facilities, models of the M557A and M557B were tested. In the U.S. $\frac{1}{10}$ and $\frac{1}{5}$ scale models of the M823 were tested at the NOL and NSRDC facilities, respectively. Static measurements were made at all facilities. Roll-damping and pitch-damping tests were run by RAE and pitch-damping Magnus force and moment measurements by NOL. The most significant feature of these tests has been the broad agreement between data obtained from models of differing scale tested in a wide range of facilities with working sections varying from 21 in. × 32 in. to 10 ft × 9 ft.

6. Results of Tests with Cruciform Tail Vehicles

The aims of the free-fall program were to a large extent achieved. Satisfactory correlation resulted between the aerodynamic data obtained from the inflight instrumentation and from the wind tunnels. In Fig. 4, such comparisons are based upon the normal force coefficient C_N and the pitching moment coefficient C_m. Motions observed in flight could also be well simulated using wind-tunnel data in six-degree-of-freedom computer programs. In Fig. 5, a comparison is made between the predicted (computer simulated) and the measured (free-fall trials) values of complex angle of attack. It will be observed that certainly the grosser aspects of the measured quantities have been reproduced by the computer trajectory simulation. Similar remarks can be made about the total angle-of-attack comparison presented in Fig. 6. In only one respect could no correlation be obtained between the motion

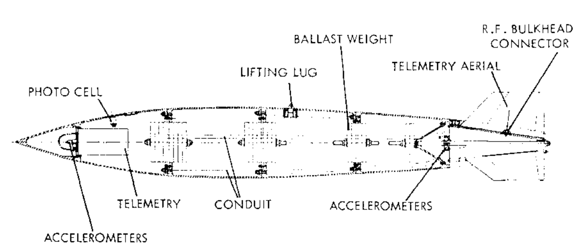

Fig. 3 WRE instrumented bomb.

observed and that predicted by the computer. This disagreement was in the roll behavior observed in two M557A rounds released at 0.5 M from 25,000 ft. At first this was believed to be due to inadequate representation of the flight Reynolds number in the wind-tunnel tests, but exhaustive tests on the M557A model at RAE indicated that the cause lay elsewhere.[10] When the wind-tunnel model was modified to include the nose probe in which the yaw meter was carried in these two rounds, it was found that the probe caused very large changes in the yaw-induced forces and moments.[11] This has been explained by the sensitivity of the shedding of asymmetric body vortices to the nose geometry.[11] One of the lessons learned from this program is that however good the wind-tunnel results, their ultimate value must depend on a faithful modeling of the flight vehicle. This is particularly true of ordnance items where surface asymmetries, e.g., nose fuzes, carriage lugs, etc., are frequently found.

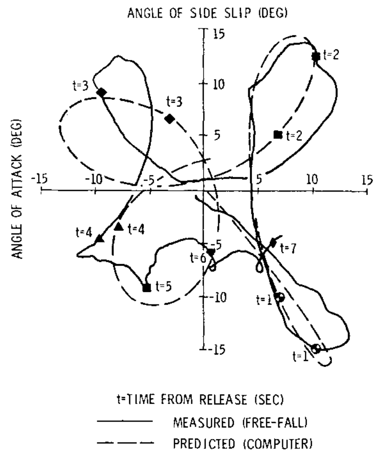

Fig. 5 Angle of attack vs angle of side slip for computer and free-fall trajectories for fixed cruciform stabilizer.

7. Novel Stabilizers

In addition to the conventional cruciform tail, other stabilizers were used with the basic M823 configuration. These other stabilizers have been indicated earlier as the split-skirt and the free-spinning cruciform and monoplane tails. The split-skirt tail is formed by splitting a cylinder axially into four parallel segments which are then opened to form a stabilizer (see Fig. 2). This type of stabilizer was thought to be advantageous because it would avoid the influence of body vortices on fins and, therefore, greatly reduce the yaw-induced forces and moments. However, the main attractiveness of this design lay in the tactical advantage of a variable drag stabilizer in a single carriage. By presetting a skirt opening prior to release, a high- or low-drag mode could be selected to meet immediate operational requirements. Wind-tunnel tests of both static and dynamic aerodynamic forces and moments have been made at NOL and two instrumented vehicles have been released over the WRE range.[9,12] These tests have shown that the lack of yaw-induced forces and moments is matched by a lack of roll damping; therefore, any roll acceleration induced by asymmetries in body or tail will rapidly build up roll frequencies to give roll lock-in. Ultimately, the roll velocity might be high enough to induce Magnus instability. Mechanical feasibility studies of possible skirt opening techniques have shown that they are complex and, hence, expensive structures. It is probable that

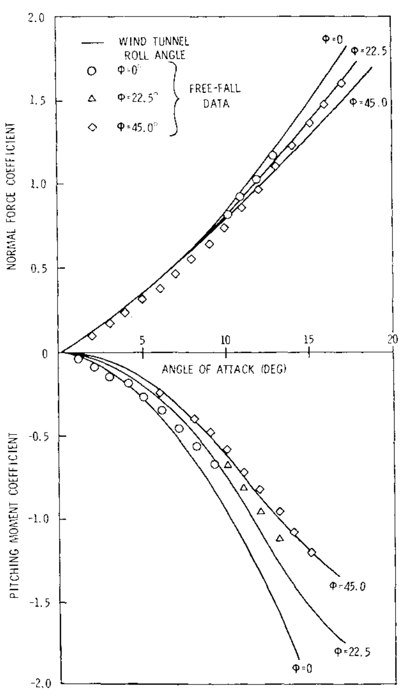

Fig. 4 Comparison of wind-tunnel and free-fall measurement of normal force and pitching moment coefficients at Mach 0.75 for the M823 research store with a cruciform stabilizer.

roll damping could be provided by strakes on the skirt although in production there could be alignment problems.

Another way in which the effects of the yaw-induced forces and moments can be reduced is to mount the aft end of the tail cone of a vehicle on a bearing and allow it to be freely spun by fin cant. Three M823 instrumented bodies were modified to carry free-spinning tails and static and dynamic wind-tunnel measurements on models with free-spinning tails have been made at RAE and NOL. The wind-tunnel data have, through the six-degree-of-freedom computer program, predicted trouble-free flight and this has been obtained in the full-scale flight trials. Excellent simulation of the bombs response to release disturbance has been obtained by the computer program. Figure 7 presents an example of this simulation. The excellent agreement is due in no small part to the virtual elimination of the roll-induced forces and moments afforded by this type of stabilizer.

The free-spinning tail concept has been taken one stage further in applying it to a monoplane tail. The monoplane tail is formed from the cruciform tail by removing two opposing fins. This stabilizer offers the same advantages as the cruciform tail with the added advantage of ease of stowage and handling of the monoplane. It must be added, however, that for the same average static stability the monoplane must have larger fin span than the cruciform, or the body center of gravity must be moved forward. Wind-tunnel test data have been provided by ARA and NOL, with the distinction that the tests at ARA were with the fin fixed and the model rolled to various orientations while the NOL tests were made with the tail freely spinning.[8,13] The round that has been dropped produced unsatisfactory results in that a large trim was observed through a significant portion of the flight. While these results have yet to be completely analyzed, it can be said that the monoplane spinning tail does not appear to offer great advantage over the cruciform spinning tail.

8. Conclusions

The program has shown that it is possible to examine the detailed behavior of a vehicle's motion by internal vehicle

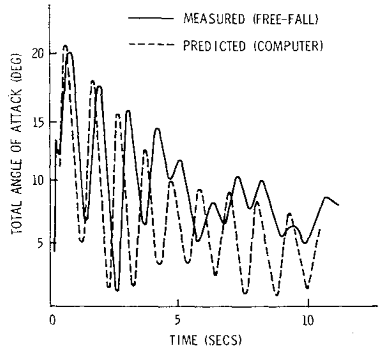

Fig. 6 Total angle of attack vs time for computer and free-fall trajectories.

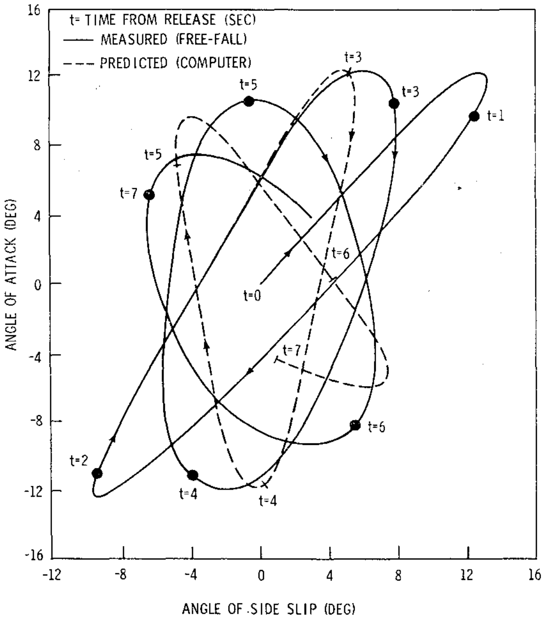

Fig. 7 Angle of attack vs angle of side slip for freely spinning cruciform stabilizer.

instrumentation and to deduce meaningful aerodynamic data from it. It has also shown that wind-tunnel tests can yield data to simulate the grosser aspects of vehicle behavior in specific instances and hence wind-tunnel data in conjunction with adequate computer programs can be used to predict acceptable missile performance. It is important to note here that wind-tunnel models must accurately represent the full-scale vehicle.

The vital importance of the yaw-induced forces and moments, particularly rolling moment, in the growth of catastrophic yaw was demonstrated early in the program. The novel stabilizer designed to avoid these forces and moments has had mixed success. It is probable that both the split-skirt and spinning monoplane tail could be satisfactory with further design work; the spinning cruciform tail, however, has shown that it is capable of overcoming these problems without developing Magnus instability.

References

[1] Rhodes, C. W. and Shannon, J. H. W., "Results and Conclusions of the Joint RAE/ARE Research Program on the Flight Dynamics and Ballistic Consistency of Freely Falling Missiles, Part 1 Bombs Stabilized by Fixed Cruciform Fins," WRE Technical Rept. HSA 20, Dec. 1965, Weapons Research Establishment, Salisbury, South Australia.

[2] Nicolaides, J. D., "On the Free-Flight Motion of Missiles Having Slight Configurational Asymmetries," BRL Rept. 858, June 1953, Ballistic Research Labs., Aberdeen Proving Ground, Aberdeen, Md.

[3] Nicolaides, J. D., "Two-Nonlinear Problems in the Flight Dynamics of Modern Ballistic Missiles," IAS Paper 59-17, June 1959, AIAA.

[4] Regan, F. J., "Magnus Effects," *The Fluid Dynamic Aspects of Ballistics AGARD Conference Proceedings*, No. 10, AGARD Fluid Dynamics Panel, Mulhouse, France, Sept. 1959.

[5] DeGrafft, W. D., "A Powered Flight Six-Degree-of-Freedom Trajectory Program for an IBM 7090 Computer," NOLTR 66-199, March 1967, U.S. Naval Ordnance Lab., White Oak, Silver Spring, Md.

[6] Secomb, D. A., "Transonic Wind Tunnel Measurements of the Effect of Roughness Bands on a Bomb with Sharp Edged Fins," ARL Rept. A213, Aeronautical Research Lab., Melbourne, Australia.

[7] "Results of Tests on a Streamline and Bluff Research Store Over the Mach Number Range 0.50–1.25 (RAE Models M577A and M577B)," ARA Wind Tunnel Test Rept. S44, Bedford, England, May 1963.

[8] Regan, F. J., Falusi, M. E., and Holmes, J. E., "Static Wind Tunnel Tests of the M823 Research Store with Fixed and Free-Spinning Tails," NOLTR 65-114, April 1967, U. S. Naval Ordnance Lab., White Oak, Silver Spring, Md.

[9] Regan, F. J., Holmes, J. E., and Falusi, M. E., "Pitch Damping Tests of the M823 Research Store with Cruciform and Split-Skirt Stabilizers," NOLTR 65–68, Oct. 1966, U. S. Naval Ordnance Lab., White Oak, Silver Spring, Md.

[10] Lee, P., "The Induced Rolling Moment Characteristics of the M557A Research Store at M = 0.50," RAE Rept. to be published, Royal Aircraft Establishment, Bedford, England.

[11] Thomson, K. D. and Morrison, D. F., "On the Asymmetric Shedding of Vortices From Slender Cylindrical Bodies at Large Angles of Yaw," WRE TN, HSA 106, May 1965, Weapons Research Establishment, Salisbury, South Australia.

[12] Regan, F. J., Falusi, M. E., and Holmes, J. E., "Static Wind Tunnel Tests of the M823 Research Store with Split-Skirt Stabilizer," NOLTR 61–89, Jan. 1966, U. S. Naval Ordnance Lab., White Oak, Silver Spring, Md.

[13] Marsden, P., "Results of Wind Tunnel Tests on the M823 Research Store with Fixed Monoplane Fins (ARA Model M25)," ARA Model Test Note M25/1, Bedford, England, Sept. 1967.