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TRANSONIC AERODYNAMIC AND SCALING ISSUES FOR LATTICE FIN PROJECTILES TESTED IN A BALLISTICS RANGE

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This paper attempts to address transonic aerodynamic characteristics and scaling issues for projectiles with lattice fins. For this work, ballistic range tests were conducted on a sub-scale, generic missile configuration in the United States Air Force Aeroballistic Research Facility located at Eglin AFB, Florida. This facility is a free-flight ballistics range used to examine the exterior aerodynamics of various projectiles. Two lattice fin configurations were tested at Mach numbers from 0.72 to 0.86. The main area of interest was the transonic region near Mach 0.8 where choking of the lattice fin cells is believed to be occurring. The results indicated a change in projectile stability in the region where choking occurs. Variations in lattice fin geometry affect the Mach number at which choking occurs.

INTRODUCTION

Lattice fins have been studied for flight vehicle control for several years. A lattice fin (or ‘grid’ fin) is an unconventional missile control surface comprising an outer frame supporting a grid of lifting surfaces. This fin design offers favorable lift characteristics at high angle of attack and almost zero hinge moments allowing the use of small and light actuators[1,2,3,4]. In addition, they promise good storability for potential tube launched and dispenser launched applications[5]. The typical drawback for lattice fins, its high drag, is currently under investigation. Some promising results have already been achieved[6].

The available data on lattice fins are mainly based on wind tunnel tests and computational fluid dynamic calculations[7,8]. However, the free-flight ballistic range has several advantages as compared to wind tunnels for aerodynamic testing. The most important one is that the test object is in unrestrained flight; therefore, no model support (sting) or wall interference effects are present during the measurement of the data. Secondly, by applying an initial starting attitude or by disturbing the flight path of the model upon launch the resulting pitch and yaw motion enables the test engineers to determine the dynamic derivatives and coefficients.

One challenge in sub-scale free flight testing of lattice fin configurations is the model design and construction. Since the model and sabot package is gun launched this package must be sized to fit the launcher and be capable of withstanding the in-gun accelerations. Therefore, the size of the models is often smaller than the corresponding full-scale configurations. This can result in very fine lattice fin construction often beyond the capability of the manufacturing process. This may result in lattice fin webs that are 2–3 times thicker than their full-scale counterparts.

In addition to the challenge of building and launching sub-scale lattice fin models is the effect of scaling. Scaling based upon Reynolds number should always be considered for aerodynamic testing. However, to the authors knowledge, no data has been reported that addresses scalability of lattice fins. It is unclear how the aerodynamics of lattice fin configurations will scale. That is, will the results obtained in the free-flight facility be representative of the full-scale flight data?

OBJECTIVES

Recent papers[9,10] have documented some of the first ever sub-scale ballistic range tests of generic missile configurations with lattice fins. The data report on drag coefficient (C_{Xo}), normal force coefficient derivative ($C_{N\alpha}$), pitch moment derivative ($C_{m\alpha}$), and pitch damping (C_{mq}). The aerodynamic data also indicate that there is a critical Mach number were the pitch moment and normal force coefficients experience high variability.

It is believed that the rapid variation of pitch moment and normal force coefficients, which occurred at Mach 0.77 for the data of Reference 10, is due to the formation of normal shocks within the individual lattice cells. This phenomenon is referred to as choking. These shocks may form in only a few cells and may be highly dependent upon location and angle-of-attack. This transonic variation in aerodynamic coefficients has not been seen in prior wind tunnel data. This suggests that either this is a phenomenon of the sub-scale tests or that this effect occurs dynamically at specific Mach numbers. In addition, the web thickness of the lattice fins for Reference 10 were 2–3 times thicker than the fall scale configuration. This increased thickness will affect the drag data[6] and will also have an impact at the Mach number where these cell shocks first form.

To help address this issue and the ‘scaling’ effect for sub-scale ballistic range tests of lattice fin configurations a follow-on series of tests were performed to those of Reference 10. In these tests, two new configurations were tested within the free-flight ballistic range. The first configuration has the lattice web thickness reduced 43% (0.004d vs. 0.007d). The second configuration has the lattice fins with comparable thickness to those of Reference 10 (0.007d), but with a decreased number of webs.

These two configurations have the same body geometry as the data of Reference 10.

The body and fin geometry are depicted in Figure 1.

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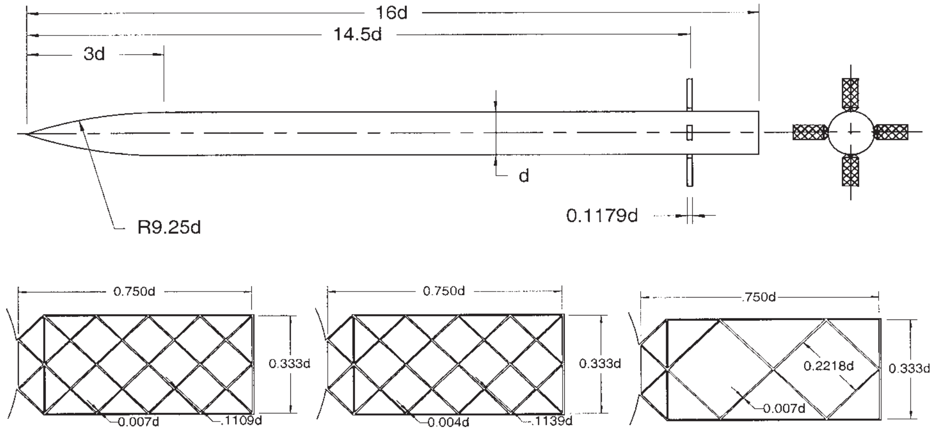

a) Baseline Fin *b) "Thin" Fin* *c) "Coarse" Fin*

Figure 1. Body and fin geometry.

EXPERIMENTAL FACILITY

The tests were conducted in the Aeroballistic Research Facility (ARF)[11]. This facility is operated and maintained by the Air Force Research Laboratory Munitions Directorate, Eglin AFB, FL. The ARF is an enclosed, instrumented, concrete structure used to examine the exterior ballistics of various free-flight projectiles. The 207-meter instrumented length of the range has a 3.66 m^2 square cross section for the first 69 meters and a 4.88 m^2 square cross section for the remaining length. The range has 131 locations available as instrumented stations of which 50 are currently used to house fully instrumented orthogonal shadowgraph stations. Besides the shadowgraph stations the facility contains one laser-lighted photographic station located in the uprange end of the instrumented section. The range is an atmospheric test facility where the temperature and the relative humidity are controlled to 22 ±1°C and less than 55% respectively. A chronograph system provides the times for the projectile at each station. These times together with the spatial position and orientation obtained from the orthogonal photographs provide the basic trajectory data from which the aerodynamic coefficients are extracted.

MODEL DESIGN AND TESTING CONDITIONS

Two models were designed and tested for this effort. Both models had exactly the same missile body with only the lattice fin configuration being different. The missile body was the same as that for Reference 10. This allows for one-to-one comparison of the data to isolate the effects of fin geometry. As shown in Figure 1, the models themselves featured a three-caliber tangent-ogive nose mounted to a 13 caliber long cylindrical shaped body. A roll pin was attached to the base of the model in order to be able to collect roll data.

Three fin configurations are depicted in Figure 1. The “Baseline” fin is that of Reference 10. The “Thin Fin” design is similar to that of the Baseline except that the web thickness has been reduced to 0.004”. The “Coarse Fin” design has similar web thickness to that of the Baseline (i.e., 0.007”) however there are fewer webs in this design. All configurations incorporate four lattice fins with a chord of 0.1179d that were mounted in a cruciform orientation. The center of gravity for all models is nominally at 7.64*d*.

RESULTS

Aerodynamic Parameter Identification

From each set of free flight motion data the aerodynamic force and moment coefficients have been extracted. The complete process is described in Reference 12. The Comprehensive Automated Data Reduction and Analysis System (CADRA)[13] is usod to read the film and calculate the trajectory. The trajectory matching process is accomplished using the Aeroballistic Research Facility Data Analysis System (ARFDAS)[12,14].

Each model trajectory obtained in the ARF was initially analyzed separately, then combined in appropriate groups for simultaneous analysis using the multiple fit capability. This provides a common set of aerodynamics that match each of the separately measured position-attitude-time profiles. The multiple fit approach provides a more complete spectrum of angular and transnational motion than would be available from any one trajectory considered separately. This increases the probability that the determined coefficients define the model’s aerodynamics over the entire range of test conditions.

Aerodynamic Results

For all coefficients and derivatives the reference length is the model diameter (d) and the reference area is the cross section area of the model (A).

The zero yaw axial force coefficient (C_{X_0}) versus Mach number determined from the flight data is shown in Figure 2. The shaded symbols are the results of matching multiple flight trajectories to a common set of aerodynamics. The drag data indicates that there is a 16% drag reduction for the “thin” fin lattice and a 22% drag reduction for the coarse fin lattice as compared to the baseline configuration of Reference 10. This is not unexpected as the drag is directly related to the thickness of the webs and the number of webs present.

Figure 3 shows the pitching moment coefficient derivative $(C_{m\alpha})$ as a function of Mach number. Here it is seen a definite discontinuity in the lattice fin pitch moment coefficient derivative near Mach 0.8. There appears to be a slight shift in the Mach number for this discontinuity for both the thin fin and coarse fin data as compared to the baseline data.

Figure 4 contains the normal force coefficient derivative $(C_{N\alpha})$ versus Mach number. The lattice fin results are relatively flat; indicative of lattice fin behavior[4]. Here again it is noted there is a decrease in the normal force coefficient derivative for that data around Mach 0.8. Similar to the pitch moment data, there appears to be a slight increase in the critical Mach number that the discontinuity is occurring for the current data as compared to Reference 10.

Figure 5 contains the computed center of pressure (CP) data for the current and baseline lattice fin data. The center of pressure is calculated by the following equation:

$$\frac{X_{c.p.}}{L} = \frac{X_{CG}}{L} - \frac{C_{m\alpha}}{C_{N\alpha}}\frac{d}{L}. \qquad (1)$$

Here again a shift in the Mach number is seen for the CP discontinuity as originally seen in Reference 10. The dynamic stability derivatives *(C_{mq})* were also obtained during these tests but were not presented in this paper. Some anomalies were observed in the dynamic stability of the configuration and will be discussod in a future paper.

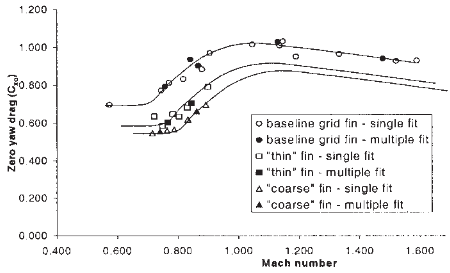

Figure 2. Zero yaw drag coefficient.

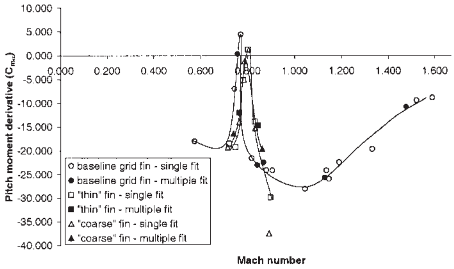

Figure 3. Pitch moment coefficient.

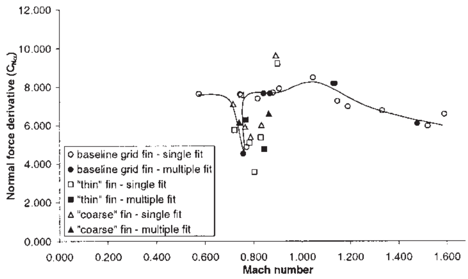

Figure 4. Normal force coefficient.

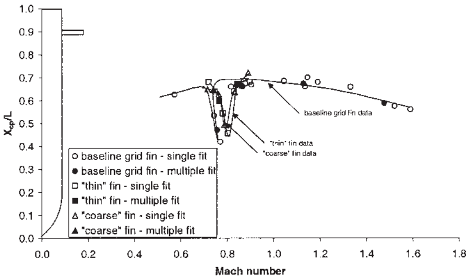

Figure 5. Center of pressure location.

DISCUSSION

For the current "thin" fin and "coarse" fin data there is again a rapid variation in center of pressure location near Mach 0.80 similar to the baseline data of Reference 10. The experimental data from the free-flight tests accurately defines the critical Mach number. A slight increase in the critical Mach number was observed for both the thin and coarse fin data versus the baseline lattice fin.

This is analogous with the variation of choking Mach number with area ratio in one-dimensional internal flow (e.g., Equation 5.20 in Reference 15). The area ratios for the current data are shown in Table 1. Here, the area ratio is defined as the area between the

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webs divided by the area of the cell defined by the web centerline. Also shown in Table 1 are the observed and calculated critical Mach numbers (i.e., the onset of choked flow within the lattice cells) for the baseline and current data. In addition, the critical Mach number is given for a representative full-scale lattice fin. Although the calculated and experimental critical Mach numbers do not agree, the trend is consistent. Recall that the calculated critical Mach number is for one-dimensional internal flow, which helps explain the difference as the current lattice fin data is a more complex, two-dimensional flow.

This indicates that the variation in pitch coefficient and normal force derivative is indeed related to the choking phenomena for lattice fins. That is, with thinner webs or coarse web distribution in a lattice fin, the Mach number that choking occurs will be higher. However, due to the limitations of lattice fin manufacturing for the current tests, the area ratio of the lattice fins is not preserved. This causes the onset of choking to occur at a lower Mach number than a full-scale configuration. This phenomenon will also be affected by boundary layer growth along the web walls for the various configurations that will cause a slight change in the critical Mach number.

Table 1: Critical Mach numbers for fin choking

Configuration	Nominal Cell Width	Web Thickness	Area Ratio $((w-t)^2/w^2)$	M_{cr} observed	M_{cr} calculated
Baseline	.1179d	.007d	0.885	.77	.655
“Thin” fin	.1179d	.004d	0.933	.80	.735
“Coarse” fin	.2288d	.007d	0.940	.80	.748
Full scale	.2d	.0015d	0.985	-	.870

The issue remains as to why a variation in center of pressure location is observed around the critical Mach number (i.e., the onset of cell choking). With the exception of some recent wind tunnel tests[16], this phenomenon has not been observed in prior testing. There are two possible explanations to this fact. First, if this phenomenon occurs over a small Mach number regime at/around the critical Mach number, then the prior tests would have required a very refined control on Mach number. Typically, wind tunnel tests are conducted at discrete Mach numbers so this phenomenon could have easily been missed. Second, these free-flight tests represent the only known measured dynamic flight data for a lattice fin configuration. There could be some transient dynamic effects occurring in the free-flight tests that would not be observed in the typically steady state testing of wind tunnels. For instance, if the configuration is near the critical Mach number, there could possibly be choking and unchoking of the lattice cells as a function of angle of attack variations. Another possibility is that the choking of the lattice fins produces a reduced pressure field acting on the missile body aft of the fins thus causing the center of pressure to move forward.

CONCLUSIONS

Aerodynamic force and moment coefficients have been extracted for a “thin” and “coarse” lattice fin missile configurations and are compared with baseline lattice fin data. The Mach number regime for these tests varied from 0.72 to 0.86. This Mach number regime corresponds to a region of high variability as observed in the baseline configurations.

The zero-yaw axial force data indicated a reduction of 16% for the “thin” lattice fin data where the web thickness was reduced from 0.007d to 0.004d. The drag reduction was reduced 22% for the “coarse” lattice fin where the web thickness remained at 0.007d but the cell size was increased from 0.1179d to 0.2288d.

A rapid loss of stability was observed at what is referred to as the critical Mach number. Little difference was seen in the pitch moment and normal force coefficient comparing the thin and coarse fin data. However, the severe perturbation in the normal force, pitch moment, and center of pressure was observed for the current data and this occurred at a slightly higher Mach number versus the previous baseline data (0.80 vs. 0.77). This observed variation in center of pressure seems to correspond to the critical area ratio for the lattice cells. This fact needs to be considered when conducting scaled lattice fin tests.

The severe variation in center of pressure observed in the current and baseline tests can be attributed to either the possible choking and unchoking of the lattice cells due to the dynamic motion of the missile around the critical Mach number or a reduced pressure field acting on the missile body immediately behind the fins. Both of these possibilities should be investigated further by either experimental or computational means.

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