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MAGNUS INSTABILITIES AND MODELING FOR A 12.7 mm PROJECTILE WITH ROLL DAMPING FINLETS FROM FREE-FLIGHT TESTS AT MACH 1.7

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Free-flight tests were conducted in the Defence Research Establishment Valcartier (DREV) aeroballistic range on a spinning projectile with roll damping finlets at Mach 1.7. All the main aerodynamic coefficients and dynamic stability derivatives as well as nonlinear one were very well determined. One projectile damped naturally while two others showed a limit cycle amplitude. High order Magnus moment coefficient terms explained the measured angular motion. A comparison, with and without the high order Magnus term, was conducted to explain the flight dynamic behavior. A dynamic stability analysis was also performed to explain the motion.

INTRODUCTION

The use of small finlets on projectiles to reduce the spin in flight in a controlled manner offers possibilities for range limited rounds. This technology involves modifying the spin stabilized projectile to decrease the spin rate in a controlled manner so that the onset of gyroscopic instability occurs at a specified range, usually the effective range of the in service round. Afterwards, the instability causes the projectile angle of attack to increase, which may lead to the tumbling, causing very high drag, thus limiting the maximum range. The fins must be carefully designed so that the projectile becomes unstable at the desired range. The onset of gyroscopic instability depends primarily on the length and height of the fins as well as their location on the projectile.

Having small finlets at the aft end of the projectile causes the flow to be modified significantly and various free-flight tests [1–5] have shown that a high Magnus moment results. The Magnus moment, in many cases, was highly nonlinear. Magnus instabilities were noticed in some instances leading to projectiles flying with a high amplitude limit cycle.

At one particular Mach number, the angular motion of three projectiles fired at the same Mach number showed different angular motions. Two were fired with a high initial angle of attack of 15.0° and one at roughly 8.0°. The angle of attack history for the projectile fired at the low angle of attack damped normally while the two projectiles fired at 15.0° angle of attack damped initially and reached a limit cycle amplitude of about 5.0° at the end of the range (Fig. 1). The limit cycle was identified as Magnus Instability.

Since one projectile damps and the other two do not, this suggests a flight dynamic behavior dependant on the initial angle of attack. When the shots were solved individually, the Magnus characterization for the shot at low angle of attack was completely different from the ones fired at the high angles of attack. When the three shots were solved simultaneously in a multiple fit data reduction, the best fit was obtained when a fifth order Magnus coefficient expansion was utilized.

The complete aerodynamic coefficients obtained for this configuration at Mach 1.7 is provided. A comparison of the results of the single and multiple fit data reductions, with and without the fifth order Magnus term, will be explained to provide insight in the instability aspects, flight dynamic behavior and the limitations of the expansion that was utilized for the Magnus moment.

MODEL CONFIGURATION

The projectile configuration that was studied is presented in Fig. 2. The ogive of this rear fin configuration has a radius of 8.92 cal of 2.01 cal in length with a meplat diameter of 0.16 cal. The ogive was followed with a short cylindrical length of 1.23 cal. The rear of the projectile continued with a 5° boattail with a length of 0.45 cal. Four sub-caliber rounded fins were located at the rear of the boattail on a 1.13 cal long cylindrical section with a total fin span of 0.92 cal. The total length of this configuration was 4.82 cal with a center of gravity positioned at 2.64 cal from the nose tip. The fin thickness at the extreme diameter was 0.13 cal. The details of the fin geometry are given in [2]. The projectiles were made of steel and the physical properties are given in Table 1.

EXPERIMENTAL FACILITIES and DATA ANALYSIS

DREV Aeroballistic Range

The Defense Research Establishment Valcartier (DREV) Aeroballistic Range [6] is an insulated steel-clad concrete structure used to study the exterior ballistics of various free-flight configurations. The range complex consists of a gun bay, control room and the instrumented range. Projectiles of caliber ranging from 5.56 to 155 mm, including tracer types, may be launched. The 230-meter instrumented length of the range has a 6.1-m square cross section with a possibility of 54 instrumented sites along the range. These sites house fully instrumented orthogonal shadowgraph stations that yield photographs of the shadow of the projectile as it flies down the range.

Data Analysis

Extraction of the aerodynamic coefficients and stability derivatives is the primary goal in analyzing the trajectories measured in the DREV aeroballistic range. This is done by means of the Aeroballistic Range Data Analysis System (ARFDAS, [7]). The data analysis consists of linear theory, 6 DOF single- and multiple-fit data reduction techniques with the Maximum Likelihood Method to match the theoretical trajectory with the experimentally measured trajectory. The MLM is an iterative procedure that adjusts the aerodynamic coefficients to maximize a likelihood function. The application of this likelihood function eliminates the inherent assumption in least square theory that the magnitude of the measurement noise must be consistent between parameters (irrespective of units). In general, the aerodynamic coefficients are nonlinear functions of angle of attack, Mach number and roll angle.

The 6DOF data reduction system can also simultaneously fit multiple data sets (up to five) to a common set of aerodynamics. Using this multiple-fit approach, a more complete range of angle of attack and roll orientation combinations is available for analysis than would be available from a single flight. This increases the probability that the determined aerodynamic coefficients define the model's aerodynamics over the entire range of test conditions.

The aerodynamic data presented in this paper were obtained using the fixed-plane 6DOF analysis with both the single- and multiple-fit data correlation techniques. The equations of motion have been derived in a fixed-plane coordinate system with Coriolis effects included. The formal derivation of the fixed-plane model is given in [8].

For example, the aerodynamic moment in the pitch plane is defined as [7]:

$$m = \bar{q}Ad[\overline{C}_{m\alpha}\ \frac{w}{V} + \frac{qd}{2V}\overline{C}_{mq} + \frac{pd}{2V}\overline{C}_{np\alpha}\ \frac{v}{V}]$$

The aerodynamic coefficients and derivatives are assumed to be nonlinear functions of Mach number, sine of the total angle of attack, and the aerodynamic roll angle. The assumption is made in a general sense in defining a generalized aerodynamic math model. Again as an example, the Magnus moment coefficient expansion is given by [7]:

$$\overline{C}_{np\alpha} = C_{np\alpha} + C_{np\alpha_3}\varepsilon^2 + C_{np\alpha_5}\varepsilon^4;\ \varepsilon = \sin(\text{total angle of attack})$$

The data reduction process involves obtaining the “right” aerodynamic model for the projectile studied with the least number of aerodynamic coefficients till the accuracy of the range is attained, if possible. Many test programs in the DREV aeroballistic range have yielded standard deviations between the theoretical determined trajectories with the reduced coefficients and the experimental one of the order of 0.1° in angle, 0.5 mm in the downrange direction, 0.3 mm in swerve and 1.0° in roll.

RESULTS AND DISCUSSIONS

The determined aerodynamic coefficients, their respective standard deviation and the standard deviation between the theoretical and experimental trajectories for the positional, angular and roll motions are given in Tables 2 and 3 for the single- and multiple-fit data reduction, respectively. All the aerodynamic coefficients are given at the average Mach number.

A coefficient that appears with a value and a (*) in parentheses directly below indicates that this coefficient was held constant. One that has a (–) in parentheses indicates that this coefficient was solved for and that the standard deviation for this coefficient is higher than 100%, that is, it does not influence the fit, and is considered undetermined. Those coefficients with numbers in parenthesis represent the standard deviation for that particular coefficient.

In some instances, the results showed more variation in C_{X0} and C_{lp} than would be expected at the same Mach number for all the configurations. This might be related to non-uniform engraving of the projectiles from the rifling of the gun tube. Therefore, the multiple-fit data reductions were conducted as follows. For a shot grouping, the values for C_{X0} and C_{lp} were held constant at the average of the single-fit results. The variations from this value were then uniquely solved for each shot. These variations are also given in the multiple-fit result tables as well as their standard deviation.

All the main aerodynamic coefficients (C_{X0}, $C_{N\alpha}$, $C_{M\alpha}$, C_{Mq}, $C_{np\alpha}$ and C_{lp}) were very well determined. It will be noticed in Table 3, that the shot C07 was also used in the data analysis of the multiple-fit. The data reduction of these three shots at Mach 1.6 provided quite a challenge. The angular motion of shot C07 showed an initial angle of attack of approximately 7.5° that damped to a small limit cycle of 1.5° at the end of the range (Fig. 1). Two shots fired (C08 and C09), at the same Mach number, show a complete different angular motion behavior than shot C07. The initial angles of attack of these two shots were of the order of 15.0° and the motion damped to a limit cycle of roughly 5.0° at the end of the range.

Normally, these three shots could be reduced in a multiple-fit data reduction if the modeling of the aerodynamic coefficients is appropriate, especially for the Magnus moment, in this case. In the previous data reduction for shot C07 [2], $C_{np\alpha}$ was determined at 1.1 (9%), while $C_{np\alpha^3}$ was deduced at –131.7 (16%), with the standard deviation in parentheses. The dynamic stability analysis conducted [2] was consistent with the observed angular limit cycle of about 1.5°. The standard deviation in the motion was acceptable at 0.3° in the angular motion, 1.0 mm and 0.7 mm in the downrange and swerve directions, respectively.

Two groups of multiple fit were used for the data reduction of these three shots. One multiple-fit group was with shot C08 and C09 and the other one with all three shots included. The only successful fit obtained for the three shots combined was when all three terms in the Magnus moment expansion ($C_{np\alpha}$, $C_{np\alpha^3}$ and $C_{np\alpha^5}$) were included in the fit. The standard deviation errors of these three coefficients are all of the order of 15%. It will also be noticed that, due to the high angles of attack obtained on two shots, many nonlinear terms ($C_{X\alpha^2}$, $C_{N\alpha^3}$ and $C_{M\alpha^3}$) were well determined. $C_{np\alpha^5}$ was kept constant at 736.0 when conducting the multiple-fit data reduction for shot C08 and C09 and the other determined aerodynamic coefficients are consistent with the multiple-fit group with the three shots. This adds some validity to the determined value of $C_{np\alpha^5}$. The standard deviation of the angular motion is of the order of 0.6, which is considered high. It is quite likely that the Magnus model as polynomial expansion past $C_{np\alpha^3}$ is not quite adequate to model the observed motion.

Most of the nonlinear aerodynamic coefficients were held constant at the multiple-fit values for the single fit data reduction for shot C07 but they were solved for shot C08 and C09. $C_{np\alpha^5}$ in the single fits was held constant at the multiple determined value of 736.0 and $C_{np\alpha}$ and $C_{np\alpha^3}$ were solved for. The reduced main aerodynamic coefficients as well as the nonlinear ones for shots C08 and C09 are compatible with the multiple-fit data reductions. On the other hand, when solved individually, the determined C_{Mq}, $C_{np\alpha}$ and $C_{np\alpha^3}$ values for shot C07 do not agree with the multiple-fit data reductions. This is probably expected since the multiple-fit data reductions are governed by two shots at high angles of attack and with a different limit cycle than the lower angle of attack shot. The standard deviation of the angular motion of the single-fits are 33% lower than the multiple-fit data reductions, further indicating that the Magnus modeling is probably not quite right.

Dynamic stability analysis

The stability plots for the projectile are provided in Fig. 3 at for two cases. The first case, Fig. 3a is for the three shots C07, C08 and C09 while Fig. 3b is for shots C08 and C09. This was done to show the consistency in the results. The limit cycle amplitudes for shot C08 and C09 at mid-range were of the order of 7.0° and shot C07 damped normally. The dynamic stability plot specifies that a limit cycle of roughly 8.0° to 9.0° should be obtained and this does not precisely match the observed motion since it is believed that the Magnus expansion model is not precise to model the observed motion, especially the fifth order term. Also, the dynamic stability analysis formulation [2] assumes linear aerodynamic coefficients and this is definitely not the case. A cubic Magnus term does predict the limits cycles quite adequately [1-4] with the linear assumptions of the formulation, but a fifth order Magnus term is probably beyond the bounds of the application.

Nevertheless the two flight dynamic modes are explained quite adequately in Fig. 3. That is, a projectile that has initial low yaws of less than 8.0° to 9.0°, like shot C07, will damp normally and those that have high initial angles of attack above 10.0°, like shots C08 and C09, will acquire a limit cycle of roughly 8.0°. The initial angles of attack for shot C08 and C09 were of the order of 15.0° while shot C07 had an initial incidence of 7.0°.

CONCLUSIONS

A series of free-flight tests were conducted in the DREV aeroballistic range to obtain the aerodynamic coefficients and stability derivatives of a 0.50 cal range limited projectile concept. This investigation was conducted to increase the database for design purposes and to validate Computational Fluid Dynamic and empirical/analytical predictions tools.

All the main aerodynamic coefficients (C_{X0}, $C_{N\alpha}$, $C_{M\alpha}$, C_{Mq}, $C_{np\alpha}$ and C_{lp}) were very well determined for this configuration and Mach number. The cubic term ($C_{np\alpha^3}$) and the fifth order term ($C_{np\alpha^5}$) in the Magnus coefficient expansion were also resolved. Nonlinear terms in the axial force ($C_{X\alpha^2}$), in the static pitch moment coefficient ($C_{M\alpha^3}$) and in the normal force coefficient ($C_{N\alpha^3}$) were well reduced.

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TABLE I

Nominal physical properties of model

d (mm)	m (g)	I_x (g-cm²)	I_y (g-cm²)	l (mm)	CG from nose (cal)
12.954	43.2	7.541	90.585	62.466	2.64

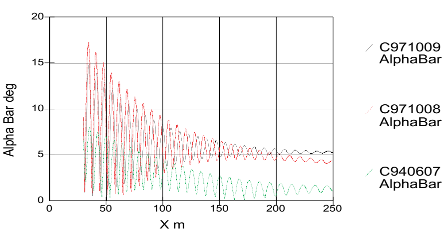
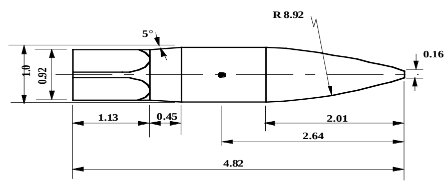


Fig. 1 – Angular motion plots.



(1 cal = 12.96 mm)

Fig. 2 – Projectile configuration.

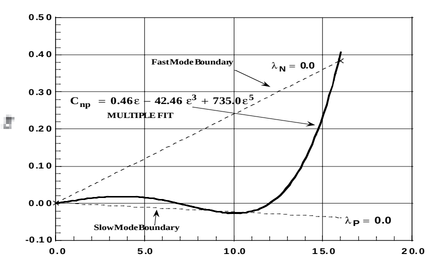


Fig. 3a – shots C07, C08 and C09.

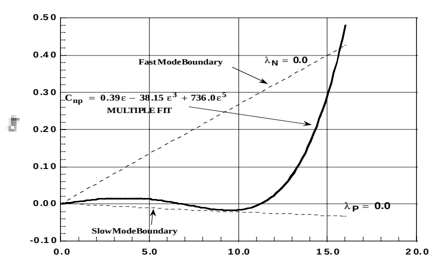


Fig. 3b – Shots C08 and C09.

Fig. 3 – Dynamic stability plots.

TABLE 2

Six-degree-of freedom aerodynamic coefficients – Single fits

Shot Number	Mach Number	DBSQ ABARM	CX CX2	CNa CNa3	CYpa CYpa3	Cma Cma3	Cmq Cmq2	Cnpa Cnpa3	Cnpa5	Clp IX/IY	CXM CmaM	Standard Error X (m) Y-Z (m)	Standard Error Angle (deg) Roll (deg)
C09	1.689	42.2	.413	3.010	–1.00	2.431	–24.5	.28		–.1488	–.01	.0004	.354
			(1.%)	(2.%)	(*)	(0.%)	(4.%)	(14.%)		(0.%)	(–)		
		14.9	–.246	21.528	.00	–2.1	.0	–31.4	736.	.0816	–.43	.0006	8.090
			(–)	(8.%)	(*)	(26.%)	(*)	(7.%)	(*)	(0.%)	(15.%)		
C08	1.726	45.1	.403	3.014	–1.00	2.424	–24.8	.42		–.1543	–.03	.0004	.398
			(0.%)	(1.%)	(*)	(0.%)	(4.%)	(9.%)		(0.%)	(47.%)		
		16.4	–.083	19.441	.00	–4.9	.0	–38.5	736.	.0815	.14	.0005	9.077
			(–)	(4.%)	(*)	(9.%)	(*)	(4.%)	(*)	(0.%)	(64.%)		
C07	1.729	7.7	.372	3.326	–1.00	2.485	–18.9	1.05		–.1675	–.12	.0005	.398
			(0.%)	(3.%)	(*)	(1.%)	(11.%)	(12.%)		(*)	(12.%)		
		7.5	4.253	23.000	.00	–5.0	.0	–144.5	736.	.0833	.14	.0005	.000
			(12.%)	(*)	(*)	(*)	(*)	(15.%)	(*)	(*)	(–)		

TABLE 3
Six-degree-of freedom aerodynamic coefficients – Multiple fits

Shot Numbers	Mach Number	DBSQ ABARM	CX CX2 CX4 ΔCX	CNa CNa3 CNa5	CYpa CYpa3	Cma Cma3 Cma5	Cmq Cmq2 Cmq4	Cnpa Cnpa3 Cnpa5	Clp CXm CmaM ΔClp	Standard Error X (m) Y-Z (m)	Angle (deg) Roll (deg)
C08 C09	1.707	43.1 16.3	.390 (*) –.414 (49.%) .00 (*)	2.936 (1.%) 23.134 (5.%) .00 (*)	–1.00 (*) .00 (*) .0 (*)	2.415 (0.%) –3.049 (15.%) 1. (35.%)	–23.6 (4.%) .0 (*) 736. (*)	.39 (10.%) –38.15 (5.%) –.323 (23.%)	–.1507 (*) –.0102 (–)	.0006 .0007	.5524 8.7230
C08			.01652 (43.%)						–.0030 (5.%)		
C09			.02435 (34.%)						.00241 (6%)		
C07 C08 C09	1.714	30.9 16.3	.380 (*) –.656 (11.%) .00 (*)	2.900 (1.%) 22.982 (5.%) .00 (*)	–1.00 (*) .00 (*) .0 (*)	2.430 (0.%) –4.113 (12.%) 1. (11.%)	–22.0 (5.%) .0 (*) 735. (14.%)	.46 (13.%) –42.46 (15.%) –.102 (76.%)	–.1681 (*) –.0133 (32.%)	.0006 .0008	.6156 7.8030
C07			–.00009 (–)								
C08			.02811 (11.%)						.01506 (0.%)		
C09			.03715 (9.%)						.02044 (1%)		