In-Flight Measurements of the Vibration History of Spin-Stabilized Projectiles

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MODERN spin-stabilized projectiles commonly contain solid but nonrigid or liquid payloads. These types of payloads often produce projectile/payload interactions that are undesirable. Vibrations of the projectile/payload assembly could impair the performance of military fuzing, especially if that fuzing is mechanical in nature. In some instances, the timer is mechanical, but normally all fuzes have mechanical arming and safety devices. Projectile designers during test sequences often report fuze malfunctions, but little is known about the vibration environment of an artillery projectile during flight. In response to this need, an instrumentation package consisting of a strain gage bridge/attitude sensor and a telemetry unit was built and successfully tested. Several types of units were flight tested and data showing undesirable vibration histories during the flight of a projectile have been recorded.[1,2] Data from 155-mm projectiles with liquid payloads are discussed.

A standard yawsonde body was modified to accommodate a Wheatstone bridge.[3] The bridge was located on a flat machined onto the cylindrical portion of the yawsonde body which extends into the ogive of a parojectile (Fig. 1). This flat was located 90 deg from the optical sensors of the yawsonde. Wires that provide voltage input and resistance measurements were located in a groove. These wires were brought through a hole in the groove to the interior of the yawsonde. The strain gages were semiconductor types and required amplification for telemetering. The output of the bridge circuit was not calibrated in such a fashion as to provide meaningful measurements of strain. Rather, the outputs of all units were adjusted for maximum sensitivity to variations in strain, i.e., vibrations. The output of the bridge circuit will be directly affected by the spin and yaw of the projectile; hence, yawsonde data are needed to interpret the vibration history of a particular projectile flight.

The angular and spin motions of a projectile are traced by a yawsonde. The projectile motion is presented in terms of σN and $\dot{\phi}$ vs time. The complement of the angle between a vector drawn to the sun and a vector aligned with the spin axis of the projectile is σN, while $\dot{\phi}$ is the derivative of the projectile's Eulerian roll angle with respect to the sun plane, i.e., the plane containing the missile's axis and the sun.[4]

The output of the strain gage bridge is an indicator of a fluctuating strain, and a spectral analysis can reveal the frequency content of these fluctuations. The presence of a particular frequency component implies that the projectile is experiencing a measurable mechanical strain at that frequency. For example, all projectiles experienced strains produced by the spin and yaw motions at the spin and yaw rates. As seen from Fig. 2, the Fourier transform of the bridge output produced frequencies below 100 Hz. Hence, the transformed data were usually displayed in a 0-100 Hz format and were free of harmonic responses of the fundamental frequencies.

Table 1 provides a comparison of the frequency of the strain and yawsonde data from four projectiles. The frequencies of motion of a projectile are the spin p, the nutation,

$$\dot{\phi}_1 = (I_x p/2I_y)(1+\sigma)$$

and the precession,

$$\dot{\phi}_2 = (I_x p/2I_y)(1-\sigma)$$

I_x and I_y are the axial and transverse moments of inertia, and σ is related to the gyroscopic stability factor.[4] For rounds 43,

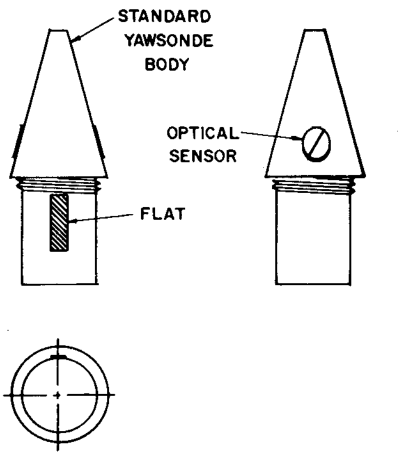

Fig. 1 Schematic of a strain sonde.

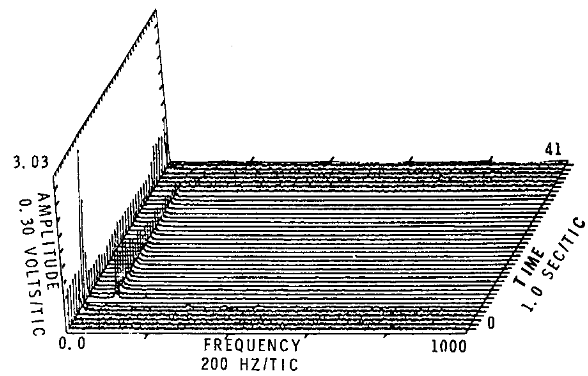

Fig. 2 Fourier analysis of strain data (frequency vs amplitude vs time) for round 43.

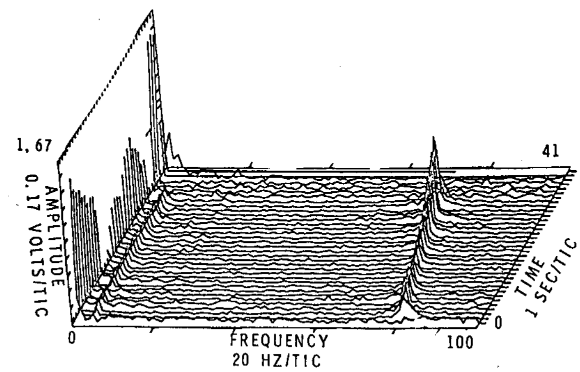

Fig. 3 Fourier analysis of strain data (frequency vs amplitude vs time) for round 47.

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Table 1 Summary of frequency content

Time, s	F1, Hz	F2, Hz	F3, Hz	Spin, Hz	$\dot{\phi}_l$,[a] Hz	$\dot{\phi}_l$,[a] Hz
			Round 43			
4.09	72.5	78.5[b]	ne[c]	78.4	...	1.0
10.24	70.3	↑	ne	76.5	6.5	1.4
16.38	68.5	|	ne	74.5	8.0	1.5
21.50	67.3	↓	ne	73.3	...	...
26.60	66.3	71.0	ne	...	...	...
		↕	Round 44			
2.04	73.5	79.2	ne	80.3	...	1.0
5.00	72.5	↑	ne	79.1	...	...
10.10	70.6	|	ne	77.2	7.0	1.4
15.20	69.4	↓	ne	75.5	6.5	1.5
19.09	68.3	73.6	ne	74.5	6.0	1.4
		↕	Round 45			
1.02	71.3	76.6	ne	84.0	...	...
8.18	71.0	↑	ne	77.2	...	...
13.30	69.4	|	5.6	75.0	...	...
17.40	68.2	|	5.8	73.5	...	...
22.52	66.8	|	ne	...	...	...
25.59	66.2	↓	ne	...	...	...
28.67	65.2	70.5	ne	...	...	...
			Round 47			
2.04	80.9	4.9	ne	80.3	6.5	1.0
5.11	79.4	4.8	ne	79.4	7.0	1.0
11.26	78.0	5.1	ne	77.4	7.0	1.5
17.40	76.1	4.9	ne	75.4	6.5	1.6
23.55	74.2	5.0	ne	...	...	...
28.67	72.5	5.0	ne	...	...	...

[a] Estimated from yawsonde data.
[b] Numerical entries joined by lines indicate a range of estimated values.
[c] Not strongly evident within the reduced data.

44, and 45, the F2 frequency component is approximately equal to p or $p-\dot{\phi}_2$. The F1 frequency response, however, closely follows $p-\dot{\phi}_l$. The measurement of a strain frequency, say s, is, of course, made onboard the spinning projectile. This frequency, when viewed in terms of an Earth-fixed coordinate system becomes $p-s$. Hence, we expect that the fundamental responses of the strain gage bridge will be $p-\dot{\phi}_l$ and $p-\dot{\phi}_2$. The frequency resolution is not sufficiently accurate to distinguish between a response of p or $p-\dot{\phi}_2$, but the actual response frequency is $p-\dot{\phi}_2$. Note that although the yawing motion is essentially steady, the spin is decreasing due to aerodynamic roll damping. Therefore, we expect $p-\dot{\phi}_l$ to decrease with time; $\dot{\phi}_l$ also varies with time, but normally not as fast as p. The variation in $p-\dot{\phi}_l$ is primarily due to the decrease in p.

The behavior observed for round 47, Fig. 3, was unlike the three other rounds and was quite unusual. This may have been expected since the liquid payloads in rounds 43, 44, and 45 were similar, but round 47 was not. The F1 component closely follows $p-\dot{\phi}_2$ and not $p-\dot{\phi}_l$, while the F2 component is approximately 5 Hz. The three other rounds had an intermittent or very weak response in the 5 Hz range. Within Table 1, the F2 response of round 47 was tracked at a very steady value of 5 Hz. This response could be produced by the liquid payload. It is also possible that this F2 response is produced by some mechanism not asociated with the liquid, perhaps the canisters which are separately keyed to the projectile body. From Table 1, the F2 response seems to follow a beat frequency of $(\dot{\phi}_l-\dot{\phi}_2)$, but there is good agreement only at the 17.4 s time frame. It is not clear from physical considerations that F2 is related to $\dot{\phi}_l-\dot{\phi}_2$, and the flight data do not strongly suggest such a conclusion. At present, the origin of the F2 response for round 47 was not produced by the yawing motion, which from the yawsonde data was damped. This type of response could provide a resonance mechanism with a fuze. In particular, a common fuze used on this projectile has a mechanical timer with an escapement mechanism that oscillates at 80 Hz.

In-flight measurements of strain and the associated vibrations in the vicinity of the ogive of spin-stabilized projectiles were made. A vibration history of one liquid-carrying projectile was quite unusual. For this projectile, a frequency component equal to the difference between the spin frequency and the precessional frequency was observed. The amplitude of this component increased dramatically in the second half of the trajectory, while the associated yawing motion measured in that region of the trajectory was quite stable. This suggests that the energy associated with these vibrations was growing, but the vibrations were not large enough to modify the motion of the projectile.

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Melting of Solid Bodies Due to Convective Heating with the Removal of Melt

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Nomenclature

- c = heat capacity per unit volume of the material
- D = thermal dissipation
- h = heat transfer coefficient
- H = heat flow vector
- k = thermal conductivity of the material
- L = latent heat of the material
- m = dimensionless thickness of the melt removal = hq_3/k
- $q_l(t)$ = unknown surface temperature
- $q_2(t)$ = unknown penetration depth
- $q_3(t)$ = unknown thickness of melt removal
- Q = thermal force
- S_t = inverse of Stefan number = $\rho L/cT_m$
- t = time
- T = temperature
- V = thermal potential
- x = direction in which heat is applied

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