Measurement of electromagnetic launcher muzzle velocity with induced voltage of B-dot probe

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1 Introduction

Recently (early 2013), LS-DYNA has released EM module to solve transient electromagnetic-structural coupled problem. The 'transient' means that this software is able to consider shape, deformation and movement of objective model. Until now, there is few commercial software what supports electromagnetic-structural coupled transient problem despite of much necessity. Especially, to facilitate the coupled transient problem, LS-DYNA adopts boundary element method (BEM) what does not need air field mesh manually. By supporting this ability, eddy current, induced heating and resistive heating problems in transient can be successfully and easily solved. In this paper, by using LS-DYNA EM, conduct B-dot probe performance prediction as install positions and directions. Also, measrue muzzle velocity of an electromangetic laucher by the probe.

To generate hypervelocity, an electromagnetic launcher (EML) is the best choice among a lot of apparatus. Usually, a light gas gun is widely used to obtain high velocity (~5km/s). The biggest problem of a light gas gun is that it requires huge space to install and operation. When the gas is expended from high pressure to low pressure, the gas's volume is increased dramatically. However an EML needs tinier space than light gas gun although its performance is similar. Although this big advantage, it is difficult that measure muzzle velocity of an EML by using high speed camera. To overcome this drawback, B-dot probe is essential measurement to understand the launcher's performance. A B-dot is a small cylindrical coil what is generated an induced voltage proportional to the time rate of change of the magnetic field component with parallel to the coil axis. [1,2]

By using the probe, projectile muzzle velocity can be measured. Also, from the numerical analysis, determine effect of B-dot probe install positions and directions like Fig. 1. Moreover, it is impossible that determine electromagnetic launcher's magnetic field, current density and Lorentz force which can be rarely measured by sensors. This numerical approach can be useful way to look into a lot of electromagnetic machine or equipment.



Fig. 1 B-dot and install position to measure muzzle velocity

2 B-dot probe

Usually, B-dot probe is installed like Fig. 2 (a) not (b). The reason is shown in Fig. 3 and Fig. 4. From Fig. 3, when the projectile is accelerated, magnetic field is generated by rails and projectile. Both of the magnetic fields can affect to B-dot probe. The resultant magnetic field affect is induced voltage in B-dot probe. As projectile is passing near B-dot probe, magnetic flux passed B-dot probe area is changed. This magnetic flux change generate induced voltage in B-dot probe. This principle is well

kwon as Faraday's law. [3] However, Fig. 2 (b) position is also magnetic field detectable position. The difference of (a) and (b) position is whether rails magnetic field affect to B-dot probe. If B-dot probe is installed Fig. 2 (a) position, projectile magnetic field affect is dominant. However, in Fig. 2 (b) position, not only projectile magnetic field but also rails magnetic field can affect to B-dot probe. Therefore, B-dot probe is usually installed at Fig. 2 (a) position.

The usual B-dot probe voltage signal is sinusoidal wave like 오류! 참조 원본을 찾을 수 없습니다.. The second voltage value '0' point time is estimated passing time of projectile. When the projectile is approaching to B-dot probe, B-dot probe income magnetic flux is increased. Then the induced voltage signal is positive signal. On the other hands, when the projectile is far away from projectile, B-dot probe income magnetic flux is decreased. Then the induced voltage signal is negative signal. The turning point from positive to negative is the passing time of projectile near B-dot probe.



Fig. 2 (a) Usually installed position, (b) Compared installed position



Fig. 3 Magnetic field distribution on rails and projectile



Fig. 4 Magnetic field distribution on only projectile



Fig. 5 Usual B-dot probe voltage signal

3 B-dot probe numerical analysis model measuring muzzle velocity

To measure muzzle velocity of electromagnetic launcher, numerical analysis model is established like Fig. 8. Rail property is cooper and size is 750mm length, 30mm height and 5mm thickness. And projectile property is aluminium 6061-T6 and size is 30mm length, 10mm height and 15mm width. Rails outer face are fixed with all of degree of freedom and projectile is just free along launching direction (Y-axis). [4] To generate Lorentz force, current is imposed by EM_CIRCUIT card which define current path by entrance and exit segment.



Fig. 6 Numerical analysis model to measure muzzle velocity of electromagnetic launcher



Fig. 7 LS-DYNA EM_CIRCUIT setting for electromagnetic launcher analysis



Fig. 8 Muzzle velocity calculation

Muzzle velocity is calculated by passing time difference and B-dot probe gap distance. The probe gap distance is 85mm. Passing time is determined by differential magnetic field of each element.

4 Measurement of muzzle velocity by B-dot probe

According to chapter 3, muzzle velocity can be measured. Fig. 9 shows differential magnetic field of each B-dot probe element. As proejctiel is accelerated, each peak is generated in sequence. Left side peak is near breech and rigth side peak is near muzzle. There are both sinusoidal and half-sinusodial volatage signal wave. These two different voltage signal are the results of whether B-dot probe element is affected by rails magnetic field or not. Also, as projectile approaching to muzzle, the peak height (magnitude) is higher. The calulated muzzle velocity is about 236.111 m/s like Table 1. Also,

the projectile velocity at final step is 250.956 m/s like Fig. 10.

The calculated muzzle velocity and projectile final step velocity show 14.845 m/s difference. This difference comes from B-dot probe install position and determination of passing time. First of all, the last B-dot probe is not installed at the nearest muzzle. Install position and muzzle distance is about 20 mm. This distance is enough to accelerate 14.845 m/s. Also, determination passing time is too much sensetive to calculate muzzle velocity. From Fig. 9, there are a lot of sinusoidal voltage wave and half-sinusoidal voltage wave. And each of wave has different passing point time. Therefore, I decide that passing point time is the peak time of each wave. This determination has fundamental error to calculate muzzle velocity. However, despite of this fundamental error, this performance prediction approach is useful way to expect electromagnetic launcher performance. Also, this numerical analysis

can look into inside of electromagnetic launcher, for example current density, magnetic field, Lorentz foece and temperature.



Fig. 9 Induced voltage of B-dot probe for each element

Table 1 Calculated muzzle velocity: 236.111 m/s

	B-dot 1		B-dot 2		B-dot 3		B-dot 4	
Time	0.00239 s		0.00282 s		0.00323 s		0.00359 s	
Passing time		0.00053 s		0.00	0.00 0.00)036 s	
Velocity		197.674 m/s		207.317 m/s		236.111 m/s		
Distance between each coil : 85 mm								



Fig. 10 Projectile velocity at final step: 250.956 m/s

5 Summary

B-dot probe is widely used to measure muzzle velocity of electromagnetic launcher. By sensing magnetic field change of projectile, induced voltage is generated in B-dot probe. Then muzzle velocity can be calculated by determining B-dot probe passing point time and B-dot probe distance. This numerical analysis just only can be available by LS-DYNA EM which supports structure and electromagnetic coupled transient analysis and eddy current problem adapted boundary element method. Although LS-DYNA EM cannot show magnetic field near air, it has the most important advantage what is reduce cost time. Therefore, LS-DYNA EM will be useful tool to predict electromagnetic launcher performance and other application.

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7 Literature

[1] Determining Railgun Plasma Current Distribution Using Jansson's Method to Deconvolve B-Dot Probe Signals, Bruno J. Evans, "IEEE TRANSACTIONS ON PLASMA SCIENCE", vol. 20, no. 4, 432-438, 1992.

[2] Design, construction, and calibration of a three-axis, high-frequency magnetic probe (B-dot probe) as a diagnostic for exploding plasmas, E. T. Everson, P. Pribyl, C. G. Constantin, A. Zylstra, D. Schaeffer, N. L. Kugland, and C. Niemann, "REVIEW OF SCIENTIFIC INSTRUMENTS", 80, 113505, 2009.

[3] Evaluation of solid armature's in-bore position, velocity, and current distribution using B-dot probes in railgun experiments, Z. Wang, J. He, S. Xia, Z. Xiao, L. Chen, Z. Cheng, M. Dong, J. Li, and P. Yan, "IEEE TRANSACTION ON MAGNETICS", vol. 45, no. 11, pp. 485–489, 2009.

[4] Experimental and numerical investigation of the high-velocity impact resistance of fiber metal laminates and Al 6061-T6 by using electromagnetic launcher, Hong-Kyo Kim, Eu-Tteum Park, Woo-Jin Song, Beom-Soo Kang, Jeong Kim, "Journal of Mechanical Science and Technology" 33, (3), 1219~1229, 2019.