AN ACOUSTIC METHOD OF EVALUATING ARTILLERY SHOTS

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This paper outlines a method of evaluating artillery shots based on recorded times of arrival of pressure disturbances at a specified configuration of measurement sensors. The method, implemented in hardware and software, has demonstrated excellent performance during maritime artillery firing at significant distances.

Keywords: evaluating artillery shots, time different of arrival (TDOA).

The problem of evaluating artillery shots to a naval surface target at long distances was considered in paper [1]. As the final solution, a method of acoustic evaluation of shooting described in paper [2], was modified and adopted. The final results of the theoretical considerations were implemented in hardware and software, and then the system operation was tested in real-life conditions of naval shooting [3].

To obtain the coordinates at which a projectile strikes a naval surface target and to determine its local velocity, the following configuration of measurement sensors on the target was used: three sensors (M_1—M_3) were placed in a line at its base, perpendicular to the projectile's path of flight; sensor M_4 was placed on the upper edge of the centre of the target; and sensor M_5 was displaced from the centre of the base of the target in the direction of fire (Fig. 1).

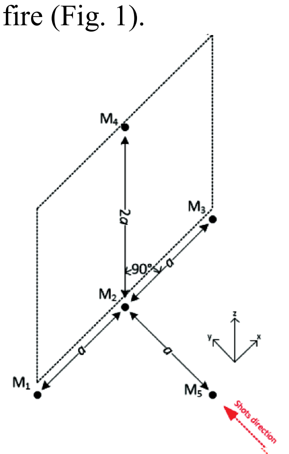

Fig. 1. Configuration of the measurement sensors on the naval surface target

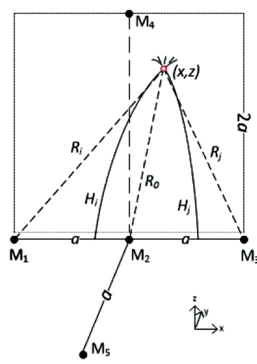

Fig. 2. Illustration of the hyperbolic method for the shot evaluation system

It is assumed that a fired projectile moves parallel to the Y axis, striking a point on the target with coordinates (x, z). It is further assumed that the calibre of the projectile and the firing distance D are known. Knowing the position of each of the sensors, and measuring the time of arrival of the front of the pressure disturbance caused by the passage of the projectile, it is possible to determine precisely the position and velocity of the projectile in the plane formed by the configuration of sensors M_1—M_4.

It is assumed that the pressure disturbance from the projectile may be treated as an infinite cone moving together with the projectile, called the Mach cone. Knowing the value of the projectile's local velocity V_p and the speed of sound c, the angle of the Mach cone can be found from the equation:

$$\alpha = \sin^{-1}\left(\frac{c}{V_p}\right) = \sin^{-1}\left(\frac{1}{M}\right), \text{ where } M = \frac{V_p}{c} \tag{1}$$

where: α — Mach angle cone [°], M — Mach number, V_p — projectile's local velocity [m/s], c — speed of sound [m/s].

It is further assumed that the target does not change its position relative to the firing position, and the velocity vector of the target is equal to that of the firing position:

$$D = \text{const} \wedge \vec{V}_t = \vec{V}_s \tag{2}$$

where D is the distance of the target from the firing position, and $\vec{V}_t$, $\vec{V}_s$ are the velocity vectors of the target and firing position respectively.

To compute the coordinates of the projectile's position, a method based on the time difference of arrival (TDOA) is adopted, using hyperbolic curves, where the characteristic pressure disturbances from projectiles reach the sensors at different times depending on the configuration of the sensors. When the front of the disturbance reaches each sensor, the time t_i is recorded, and the time differences $\Delta t_{ij} = t_i - t_j$ are then computed. Based on the measured time difference Δt_{ij} for each pair of microphones M_i, M_j, hyperbolas of ambiguity are determined (sets of all point sources which produce the same time difference of arrival of the pressure disturbance at sensors M_i and M_j). The intersections of the hyperbolas indicate the point with coordinates (x, z) at which the projectile strikes the plane of the target. To determine the point with coordinates (x, z) it is sufficient to plot at least two hyperbolic curves.

The time difference Δt_{ij} of the arrival of the disturbance between sensors M_i, M_j on the target is determined by the generalised equation of the curve H_{ij} according to the following relationship:

$$H_{ij} = \frac{\left(R_i - R_j\right)}{c} = \frac{\Delta t_{ij}}{\cos\alpha}, \tag{3}$$

where R_i is the distance of sensor M_i from the projectile in the plane of the seaborne target [m]; R_j is the distance of sensor M_j from the projectile in the plane of the seaborne target [m].

To determine the position of the coordinates of the projectile based on the readings of the sensors M_i, M_j, the cosine law is used, for which the following equation holds:

$$R_i^2 = R_j^2 + a^2 - 2R_j a \cos\theta = \left(R_j - cH_{ij}\right)^2 = R_j^2 - 2R_j cH_{ij} + c^2 H_{ij}^2, \tag{4}$$

where a is the distance between the sensors [m], and θ is the angle between the line R_j, joining the position of the sensor M_j to the point at which the projectile strikes the plane of the target, and the base of the target.

In a similar way, equations are derived for the hyperbolas of all pairs of the sensors M_i, M_j on the target. Having data for the time differences for at least three pairs of the sensors M_i, M_j, and supplementing the system of hyperbolic equations with the equation $R_0 = \sqrt{x^2 + z^2}$, referring to the geometry of the triangle formed by the displacement of the point at which the projectile strikes the target, the target's axis of symmetry and the line R_0, it is possible to determine the coordinates of the passage of the projectile through the target.

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Акустический метод оценки артиллерийской стрельбы

В статье представлен общий план оценки артиллерийской стрельбы по зарегистрированным времена возмущений давления, достигающие определенной конфигурации измерительных датчиков.
Аппаратное и программное обеспечение, реализованное в методе, оказалось идеальным во время артиллерийской морской стрельбы на значительные расстояния.

Ключевые слова: оценка артиллерийской стрельбы, метод TDOA.