16. Платонов А.В. Энциклопедия советских надводных кораблей, 1941-1945. СПб.: ООО «Изд-во «Полигон». 2002. 750 с.
17. Крылатая ракета КС-1 «Комета» // Информационно-новостная система «Ракетная техника». URL: http://rbase.new-factoria/missile/wabb/KC-1.shtml (дата обращения 23.01.2019).
18. *Lethaby J.W., Skidmore I.C.* The deformation and plugging of thin plates by projectile impact // Mech. Properties High Rate Strain. Proc. Conf. Oxford. 1974. № 21. P. 429-441.

BALLISTIC LIMIT OF A PROJECTILE IMPACTING A THIN METAL BARRIERAT A HIGH VELOCITY

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The paper uses a quasi-dynamic approach to computing impact-driven penetration effects. Then for nondeformable (poorly deformable) penetrators of an ogive-cylindrical form we may write the target fracture energy thin barriers ($h/d < 0.5$ (h, d are the barrier thickness and projectile diameter, respectively)) as [1, 2]:

$$W = \pi R^2 h \left[\frac{1}{2}\sigma_{td} + \frac{1}{16}\rho_t \pi^2 \left(\frac{V_0 R}{L}\right)^2\right] \quad (1)$$

where W is the target fracture energy; R is the penetrator radius; h is the target thickness; σ_{td} is the dynamic tensile strength of the target material; ρ_t is the target material density; V_0 is the impact velocity; L is the length of the ogive section.

By equating the energy from the expression (1) to the kinetic energy of the penetrator, we derive expressions for determining the limit thickness of the target to be perforated, the ballistic limit and the residual velocity:

$$h_{lim} = \frac{8 m_a V_0^2 L^2}{\pi R^2 (8\sigma_{td} L^2 + \rho_t \pi^2 V_0^2 R^2)} \quad (2)$$

$$V = 2RL\sqrt{\frac{2\pi h \sigma_{td}}{(8 m_a L^2 - \pi^3 h R^4 \rho_t)}} \quad (3)$$

$$V_r = \sqrt{V_0^2 - \frac{\pi R^2 h}{m_a}\left[\sigma_{td} + \frac{1}{8}\rho_t \pi^2 \left(\frac{V_0 R}{L}\right)^2\right]} \quad (4)$$

where m_a is the penetrator mass; h_{lim} is the limit thickness of the target to be perforate; V is the ballistic limit; V_r the residual velocity of the penetrator after target perforation.

This quasi-dynamic approach makes it possible to account for strength and inertial resistance of the target. As any other computational model, this approach requires comparing the results of the calculations with experimental data (in other words, validation). To validate the model, we chose the most successful use of the first guided bomb, PC-1400 FX (Fritz X) (Germany [3]), against the battleship Roma (of the Vittorio Veneto class, Italy), causing the battleship to sink. According to a US technical report [4], Fritz X, the world's first guided bomb, had a diameter of 558.8 mm and its total mass was approximately 1650 kg.

The first guided bomb perforated the ship and exploded in the water underneath the hull. The second guided bomb exploded inside the ship and sank it. We used [5-7] to design the target layouts required to compute the effects of a guided bomb. Vittorio Veneto class battleships used heavy homogeneous armour of the AOD type and heavy-duty structural ER steel [7].

We must emphasise that the relative thicknesses of the barriers perforated are either low ($h/d < 0.5$) or very low ($h/d < 0.1$), and the total target thicknesses all lie in the range of thin barriers ($h/d < 0.5$). It is possible to compute the time it takes for the guided bomb to move inside the ship, taking into account velocity losses incurred during target penetration. The barrier perforation time is relatively low; disregarding it, we obtain the delay time of the fuse installed in the guided bomb: $t_1 > 0.082$ s (motion in water not taken into account) and $t_2 = 0.084$ s. It should be noted that the results of the computation are in agreement with the descriptions of how the Roma battleship sank [5-7]. Unlike the first guided bombs, contemporary AVs are deformable. High-speed impact processes are complex enough to require experimental studies. To further validate the model proposed, we used experimental data on the precursors to anti-ship missiles, that is, airplanes with aerial bombs suspended. In this case, a kamikaze pilot is equivalent to the missile's guidance system, and the aerial bomb functions as the warhead. Moreover, not only the aerial bomb but its carrier both came into contact with the target and entered the interior volume of the target, the target being a surface combatant of the USA Navy and other Allied forces.

This led us to consider the Mitsubishi A6M Zero (Zeke), the main carrier-based fighter of the Japanese Navy during the World War II. The Zeke fighters were equipped with an air-cooled radial engine, which are to this day widely used in single-engine piston airplanes [8]. This determined their design [9] with the front face of the fuselage nose being almost completely flat. For the same reason, other airplane types used by kamikaze pilots were of similar designs.

Then in order to compute impact-driven AV penetration effects we may represent it as an equivalent cylinder of a diameter equal to the maximum cross-section diameter of the AV fuselage (fig. 1 [10]).

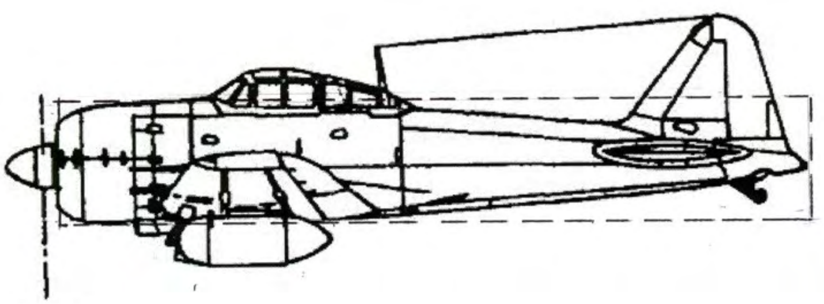

Figure 1. Layout of the cylinder equivalent to the Mitsubishi A6M Zero fighter (Japan) [10]

When substituting an equivalent cylindrical rod for an AV, we must determine the equivalent cylinder mass. Only the "dry" AV mass (no fuel) is taken into account, minus the mass of wings and empennage, since these may get cut off in the process of interacting with the target and thus will not contribute to target perforation. We consider the least favourable perforation circumstances. We also account for the fact that an AV is deformable in the case of high-velocity impact.

Let us consider a mathematical model for a cylindrical rod equivalent to an AV impacting a thin metal barrier. A first-order quasidynamic approach [1], which takes into account not only strength but also inertial resistance of the target, makes it possible to derive perforation energy for a thin metal barrier in the following way [10]:

$$W = \frac{1}{2}\pi d h^2 \tau_{td} + \frac{1}{8}\pi d^2 h \rho_t V_0^2 \quad (5)$$

where W is the energy of fracturing a target with a thickness of h by a non-deformable cylinder with a diameter of d, according to the quasidynamic approach; τ_{td} is the dynamic shear strength of the target material; ρ_t is the target material density; V_0 is the impact velocity.

By equating the expression (5) to the kinetic energy of the cylinder E, we derive an expression for the ballistic limit of perforating a thin metal barrier. Moreover, we may obtain an expression for the maximum thickness of a thin metal barrier that can be penetrated. It is evident, however, that these expressions are only valid for a non-deformable cylinder, while in the case of high-velocity impact AVs are deformable. While using numerical simulation to solve similar problems, we discovered that the work expended on deformation and fracture of a thin metal barrier agrees within 10% with the work expended on deformation of the penetrator. Then we may account for the AV structure deforming the following way [10]:

$$W = \frac{E}{2} \tag{6}$$

$$V = 2\sqrt{\frac{\pi d h^2 \tau_{td}}{2m - \pi d^2 h \rho_t}} \tag{7}$$

$$h_{lim} = \frac{\sqrt{\pi^2 d^4 \rho_t^2 V_0^4 + 32 m V_0^2 \pi d \tau_{td}} - \pi d^2 \rho_t V_0^2}{8 \pi d \tau_{td}} \tag{8}$$

$$V_r = \sqrt{V_0^2 - \frac{\pi d h}{m}\left(2h\tau_{td} + 0.5 d \rho_t V_0^2\right)} \tag{9}$$

where V is the ballistic limit; m is the reduced mass of the AV; h_{lim} is the maximum thickness of a thin metal barrier that can be penetrated; V_r is the residual velocity after target perforation.

The paper validates our model by comparing analytical computation results using expressions (8, 9) to experimental data found online on kamikaze airplanes attacking ship targets unsuccessfully [11-13] or successfully [14, 15]. The ballistic limit values computed according to our model agree with the existing data on perforation and non-perforation of ship targets by single-engine piston airplanes.

The speeds of kamikaze airplanes considered above (up to 120 m/s) are much lower than those of rockets. Due to this, in order to perform a complete verification, we shall consider the case of Krasnyi Kavkaz, a light cruiser, being fully perforated in tests of the KS-1 Komet missile (winged projectile) [16, 17]. Residual velocity computation results according to the equation (9) confirm complete perforation. Moreover, after passing through two barriers, the missile retains a signification portion of its kinetic energy, namely 67 % (a residual velocity of 275 m/s) of the initial value.

The analytical approach proposed makes it possible to use a first-order energy-based evaluation of whether the ship target (a screen) will be perforated or not, estimating the residual velocity of a deformable penetrator as well.

The analytical expressions validated for single-engine piston airplanes and KS-1 Komet missile are also valid for other AVs, since the penetration and perforation processes in these cases are similar in terms of mechanics.

We propose to implement a preliminary computational method the following way. The method's input data: M_f is the onboard AV fuel and oxidiser mass; M_0 is the take-off AV mass; V_0 is the cruising speed of the AV; σ_t is the target material yield strength; h is the target thickness; ρ_t is the target material density (ρ_t= 7800 kg/m^3 for steel).

These data may be taken from reference material [9] or computed using the visual representations of the AV designs.

Computation steps (algorithm).

1. Determining the diameter and mass of the AV-equivalent cylinder.

d, the maximum fuselage cross-section diameter, should be either measured off the technical drawings or diagrams available or taken from reference material.

$$d = \frac{L}{L_d} d_m \tag{10}$$

where L is the AV length; L_d is the AV length according to the technical drawing or layout diagram; d_m is the maximum fuselage cross-section diameter according to the technical drawing or layout diagram.

The mass of the AV-equivalent cylinder m is determined using reference data and calculations using data found in layout diagrams

$$m = M_0 - M_f - kM_0 \tag{11}$$

where k is a design-based coefficient that accounts for the mass of the wings and empennage, which may get cut off during penetration.

2. Determining impact velocity.

We assume the impact velocity to be equal to the cruising speed V_0.

3. Determining yield strength for the target material under dynamic loading.

σ_{td} – dynamic tensile strength of the barrier material may be computed using the expression [18]

$$\sigma_{td} = 1.25\sigma_t \tag{12}$$

This ratio is characteristic of ductile armour steels.

τ_{td} – dynamic shear strength of the target material, computed using the equation

$$\tau_{td} = \sigma_{td}/\sqrt{3} \qquad (13)$$

4. Computing the ballistic limit, the maximum thickness of a thin metal barrier that can be penetrated and the residual velocity.

In order to evaluate the impact-driven penetration effects we use expressions based on the quasidynamic approach for thin barrier (screens) [1, 2], taking into account the fact that the AV [10] structures are deformable in the case of high-velocity impact (7-9).

We use the equation (7) to compute the ballistic limit. If the impact velocity V_0 exceeds the ballistic limit V (that is, $V_0 > V$), then perforation occurs, otherwise we are dealing with non-perforation.

The maximum (limit) thickness of the target (screen) to be penetrated is computed using the equation (8). If the target thickness h) exceeds the computed limit value h_{lim}, (that is, $h > h_{lim}$), then there is no perforation, otherwise perforation occurs.

If penetration occurs, then the equation (9) may be used to compute the residual AV velocity after target perforation. The computed residual velocity is assumed to be the impact velocity when the AV comes into contact with the next target (screen), and the computation repeats.

The paper presents a method that makes it possible to estimate the impact-driven penetration effect of AVs that may interact with thin metal barriers either as an emergency situation or as part of their regular functionality (h/d < 0.5). We validated the method for various AVs (poorly deformable and deformable) at a wide range of velocities (from 79.3 m/s to 315 m/s). The results obtained may be used for preliminary evaluation of nuclear station protection designs employing metal screens, as well as for estimating AV dynamics during terminal ballistics.

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References

1. W. T. Thomson, An Approximate Theory of Armor Penetration (Santa Monica, RAND Corporation, 1953), available at https://www.rand.org/pubs/research_memoranda/RM1160.html.
2. A. Brown, Int. J. Mech. Sci. **6-4**, 257-262 (1964).
3. Military history. German air-to-surface missiles 1939-45, available at http://militarynavalhistory.net/articles/sakhal/german_air-to-surfase_missiles_1939-45.
4. German Explosive Ordnance (Bombs, Fuzes, Rockets, Land Mines, Grenades and Igniters) (Washington, United States Government Printing Office, 1953), available at http://www.scribd.com/doc/67488065/TM-9-1985-2.
5. S.I. Titushkin, Vittorio Veneto Class Battleships, in Ships and Battles (Saint Petersburg, GIPP Iskusstvo Rossii, 1995).
6. A.B. Shirokorad, History of Aviation Armament. Short Report, edited by A.E. Taras (Minsk, Harvest, 1999), available at https://www.litmir.me/bd/?b=276316&p=1.
7. S.A. Balakin, A.V. Dashyan, S.V. Potyanin, M.Yu. Tokarev and V.N. Chausov, Battleships of World War II: the Attack Force of the Fleet (Moscow, Kollektsiya: Yauza: EKSMO, 2006).
8. Yu.V. Makarov, Aircraft of the Moscow Aviation Institute (Moscow, Moscow Aviation Institute Publ., 1994).
9. Sky Corner, the Big Encyclopedia of Aviation, available at http://www.airwar.ru/other/draw/.
10. V.I. Pusev and V.A. Markov, Military Enginery. Scientific and Technical Journal. Counter-terrorism technical devices. Issue 16 **5-6**, 68-73 (2009).
11. Masterok, The kamikaze trail, available at http://masterok.livejournal.com/2543685.html.
12. Mitsubishi Ki-51 Sonia. URL: http://www.windowssearch-exp.com/images/search?q=Mitsubishi+Ki-51+Sonia&FORM=RESTAB (accessed January 23rd, 2019).
13. Dashyan A.V. Korabli Vtoroy mirovoy voyny. VMS Velikobritanii [Ships of World War II. Royal Navy]. Part 1 // Morskaya kollektsiya. Prilozhenie k zhurnalu Modelist-konstruktor [Naval collection. Supplement to Model Builder and Designer magazine]. 2003. No. 4. URL:

http://wunderwaffe.ru/magazine/MK/2003.04/index.htm (accessed January 23rd, 2019).

14. USS Hinsdale (APA-120), at NavSourse Online: Amphibios photo Archive, available at http://www.navsource.org/archives/10/03/03120.htm.
15. Attack Transports. Special Attack Transports, available at http://www.istrima.com/orujie-vtoroi-mirovoi-voiny/nac.
16. Platonov A.V. Entsiklopediya sovetskikh nadvodnykh korabley, 1941-1945 [Encyclopaedia of Soviet surface combatants, 1941-1945]. Saint Petersburg: Poligon JSC Publ. 2002. 750 p.
17. Krylataya raketa KS-1 Kometa [KS-1 Komet winged missile] // Informatsionno-novostnaya sistema Raketnaya tekhnika [News and information system on Rocket Engineering]. URL: http://rbase.new-factoria/missile/wabb/KC-1.shtml (accessed January 23rd, 2019).
18. J.W. Lethaby and I.C. Skidmore, Mech. Properties High Rate Strain. Proc. Conf. Oxford 21, 429-441 (1974).

РАСЧЕТ НАГРУЗОК НА СООРУЖЕНИЕ ПРИ ВЫСОКОСКОРОСТНОМ УДАРЕ ЛЕТАТЕЛЬНОГО АППАРАТА НА ОСНОВЕ ПОДХОДА РИЕРЫ

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Рассматривается подход к определению нагрузок на сооружение при ударе летательного аппарата (ЛА), предложенный Дж. Риерой [1, 2]. Данный вопрос имеет важное практическое значение, так как конструкции зданий и сооружений атомных электростанций (АЭС) по нормам [3] необходимо рассчитывать с учетом возможного воздействия при падении самолета. Предложенный Дж. Риерой подход позволяет определить зависимость нагрузки от времени при взаимодействии «мягкого» (разрушающегося) ударника, такого как самолет на посадочной скорости, с жесткой преградой.

Согласно [2], соотношение между силой и импульсом для системы такое же, как для одной частицы:

$$F_x = \frac{dQ_x}{dt}, \tag{1}$$

где F_x – проекция результирующей силы на ось x;

Q_x – проекция полного импульса на ось x.

Пусть m – это масса, лежащая в пределах фиксированного контрольного объема S в произвольный момент времени t_a. После интервала времени $dt = t_b - t_a$ граница системы, в целом, уже не совпадает с S. Кроме того, пусть Q_{xa} и Q_{xb} обозначают импульс по оси x всей среды, заключенной в S при t_a и t_b соответственно, в то время как $dQ_{x\,in}$ и $dQ_{x\,out}$ представляют собой приток и отток импульса вдоль оси x за время dt.

Результирующая сила, действующая в контрольном объеме S, может быть выражена следующим образом:

$$F_x = \frac{Q_{xa} - Q_{xb}}{dt} + \frac{dQ_{x\,out} - dQ_{x\,in}}{dt}. \tag{2}$$

Упрощенная модель «мягкого» ударника, введенная в [1, 2], предполагает наличие двух зон: пренебрежимо тонкой «деформационной» зоны, прилегающей к поверхности преграды в пределах