Investigation of Aerodynamic Characteristics for Various Types of a Lander to the Venus Surface

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Abstract. This paper discusses alternatives to the traditionally used ballistic type of a lander on the Venus surface, as well as a comparative analysis of these landers carried out by operational design evaluation of the aerodynamic forms of the landers. The calculation of the aerodynamic characteristics for the various types of a lander is presented using the numerical method according to the Newton's theory of hypersonic flow. It is proposed the perspective aerodynamic form of the lander than have certain lift-to-drag ratio and capable of making controlled descent and landing in the required area on the surface of Venus. It is demonstrated that using this aerodynamic form of a lander results in reducing the overload for ensuring the integrity of the equipment during the descent in the atmosphere of the planet and reducing aerodynamic heat fluxes compared to the ballistic type of a lander.

INTRODUCTION

The exploration of Venus as a terrestrial planet is interesting not only from the standpoint of fundamental science, but also from the standpoint of comparative planetology [1, 2].

Thanks to the results of Venus exploration in the past using spacecraft or automatic interplanetary stations as they were called at that time: Soviet spacecraft of “Venera” and “Vega” series [3, 4], American spacecraft of “Mariner”, “Pioneer-Venus” series, “Magellan” and some other flyby missions [5, 6, 7] and more recent spacecraft of other agencies: Japanese spacecraft “Akatsuki” [8], the spacecraft of the European Space Agency “Venus Express” [9], numerous scientific data were obtained, including the results of soil research and unique data on the composition and profile of the atmosphere and cloud layer and radar data about mapping the planet, and images of the surface and cloud cover, and measuring the magnetic field and ionosphere, etc.

However, despite the impressive results of previous missions, many questions still need to be answered. Nowadays to continue the fundamental Venus research, Russian-American project “Venera-D”, intended for the comprehensive study of the planet using an orbiter and a lander as main components, as well as atmospheric probes and other additional mission elements, is being developed [10, 11]. It is also worth mentioning ESA project on developing the “EnVision” orbiter [12] and NASA “Venus Flagship” mission [13]. In addition, NASA representatives selected four missions from the Discovery program for developing new conceptual studies, among which “VERITAS” and “DAVINCI +” are proposed to be designed for Venus exploration [14].

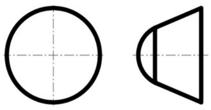
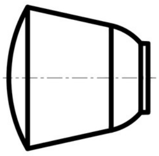
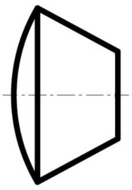
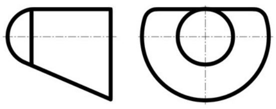
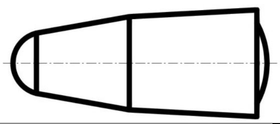
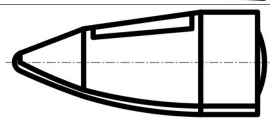
Creating a lander on the Venus surface is a complicated technical task due to its “severe” conditions near the surface [15, 16]. In the “Venera-D” mission, the design of a lander is considered similar to the Soviet landers “Venera” and “Vega”, which have a spherical form and relate to the ballistic type of a lander with zero lift-to-drag ratio at hypersonic velocity that do not provide the possibility of making maneuvers during the descent in order to choose the required landing site. The American mission “Pioneer-Venus 2” had several probes to the Venus surface, which had conical form but still they relate to the ballistic type of a lander with zero lift-to-drag ratio at hypersonic velocity. The choice of such forms for the lander at the initial stages of the Venus exploration was associated with their primary task - to reach the surface, and at the same time maintain functioning scientific equipment as the first spacecraft to the Venus surface were crushed by pressure [3].

Currently, in addition to this primary task of achieving a surface with efficient equipment, the lander may be faced with the task of achieving the required landing site, the most interesting for research [17, 18]. So, this paper considers the possibilities of new, alternative forms of a lander that have a certain lift-to-drag ratio at hypersonic velocity range and the ability to make maneuvers in order to select and achieve the landing site most attractive for studying.

AERODYNAMIC FORMS OF A LANDER

This section provides several alternative forms of a lander (See Table 1), rational both in aerothermodynamic characteristics and controllability during the process of descent [19, 20]. These forms are presented with semiconical, disk-form of a lander and a lander of the segmental-conical form.

TABLE 1. Rational aerodynamic forms of a lander depending on the range of entry velocity into the atmosphere of Venus

Aerodynamic form of a lander	K_{hyp}	K_{fill}	K_m	$L_{lat.}$, km	**Velocity range, km / s**			
					I	**II**	**III**	**IV**
	0	1÷0.9	1	0	+	-	-	-
	0.3	0.95÷0.85	1.2	0-40	+	-	-	-
	0.5	0.9÷0.8	1.28	0-70	+	+	-	-
	0.7	0.85÷0.75	1.3	0-100	+	+	-	-
	0.8	0.85÷0.75	1.4	< 900	-	+	+	-
	1.5	0.75÷0.6	1.5	> 1000	+	+	+	+

Note
I - 7.2÷10.4 km/s – first space velocity and more;
II - 10.4÷12.5 km/s – second space velocity and more;
III - 12.5÷15 km/s – moderate hyperbolic velocities;
IV - 15÷21 km/s – limiting hyperbolic velocities;
K_{hyp} – lift-to-drag ratio at hypersonic velocity range (M>5);
K_{fill} – volume efficiency (fill factor);
K_m – comparative mass coefficient;
$L_{lat.}$ – lateral maneuver.

Table 1 shows that using the aerodynamic forms with $K_{hyp} = 1 \div 1.5$ (“lifting body” type of a lander) leads to the increase in the inertial mass of the lander structure (as it shows the coefficient K_m — a relative parameter showing the ratio of the mass of this aerodynamic form of a lander to the ballistic type of a lander), which is "payment" for increasing the maneuverability of the lander at hypersonic velocity range.

The highest density of the layout is provided for forms with fill factors tending to 1. An approximate statistically average dependence of the fill factor on geometric characteristics of a lander can be used for the purposes of the initial design analysis of the lander and can be represented by the following equation:

$$K_{fill} = 1 - 0.2 \cdot K_{hyp}^{0.975}$$

The general formula for volume efficiency, reduced to a dimensionless form, is as follows:

$$K_{fill} = 4.836 \frac{(V_{\Sigma})^{\frac{2}{3}}}{S_{\Sigma}},$$

where V_{Σ} – total lander volume; S_{Σ} – total surface area of the lander.

The landers shown in Table 1 can be divided by the value of lift-to-drag ratio at hypersonic velocity range - the ratio of the lifting force to the drag force: ballistic type of a lander with zero lift-to-drag ratio (the examples are descent vehicles "Vostok", "Voskhod" (Russia) and "Mercury" (USA) type, returnable ballistic capsules "Raduga" (Russia), "Bios" and "Discoverer" (USA)), semiballistic landers of "gliding descent" type with $K_{hyp} = 0.2 \div 0.5$ (the examples are descent vehicles of the "Soyuz" type (Russia), "Gemini", "Apollo" and the unmanned "Zond" (Russia)) and "lifting body type of a lander with $K_{hyp} = 0.8 \div 1.5$ (examples: aerospace vehicles M2-F2, HL-10, SV-5, «Asset», «Prime» and «Pilot» [21, 22, 23, 24]).

AERODYNAMIC CHARACTERISTICS FOR VARIOUS FORMS OF A LANDER

The calculation of the lander aerodynamic characteristics was done by a numerical method using the Newton flow theory, which allows acquiring reliable estimates of the aerodynamic characteristics for velocities in the hypersonic velocity range (M>5) [26, 27, 28].

For the hypersonic section of the descent, a stable position can be achieved only if the center of mass of the lander lies below the center of pressure of the aerodynamic forces and is on the line drawn along the main aerodynamic force vector C_r, which is obtained by adding two vectors: the force drag vector and lift vector (See Figure 8). We will calculate the following aerodynamic characteristics:

Body-fixed coordinate system: longitudinal C_x and normal C_y force coefficients.

Velocity coordinate system(X axis direction is along the free-stream vector V – See Figure 8):

drag C_{xa} and lift C_{ya} coefficients, lift-to-drag ratio for hypersonic velocities (M>5) K_{hyp}, coordinates of the center of pressure.

Aerodynamic coefficients can be linked by the following equations:

$$C_{xa} = C_x \cos\alpha + C_y \sin\alpha,$$

$$C_{ya} = C_y \cos\alpha - C_x \sin\alpha,$$

where α - angle of attack.

Aerodynamic quality is defined as the ratio: $K = Y_a / X_a = C_{ya} / C_{xa}$.

Figures 3-6 shows the results of calculating the aerodynamic characteristics for the aerodynamic forms based on the lander of "Vega" (sphere), "Soyuz", "Apollo", "Zarya-2" type and "lifting body" type of a lander. Various aerodynamic forms used for comparison are presented in Figures 1 and 2. The dimensions of the landers are taken so that their volume is no more than 2 m^3, which ensures the layout of all necessary scientific equipment inside weighing no more than 100 kg for the "Venera-D" mission [10, 11].

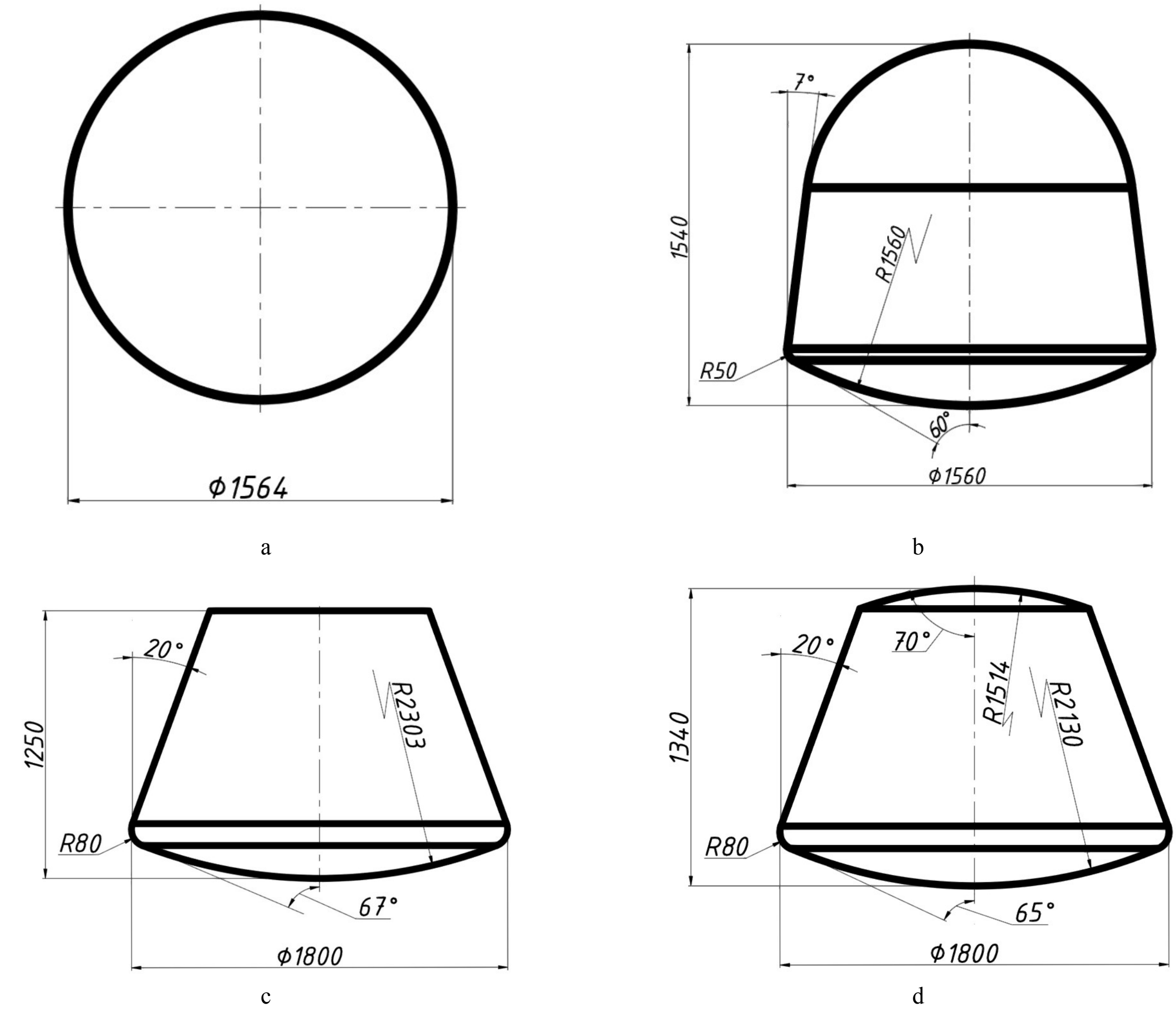


FIGURE 1. Aerodynamic forms of a lander based on “Vega” (a), “Soyuz” (b), “Apollo” (c), “Zarya-2” developed by K.P. Feoktistov (d)

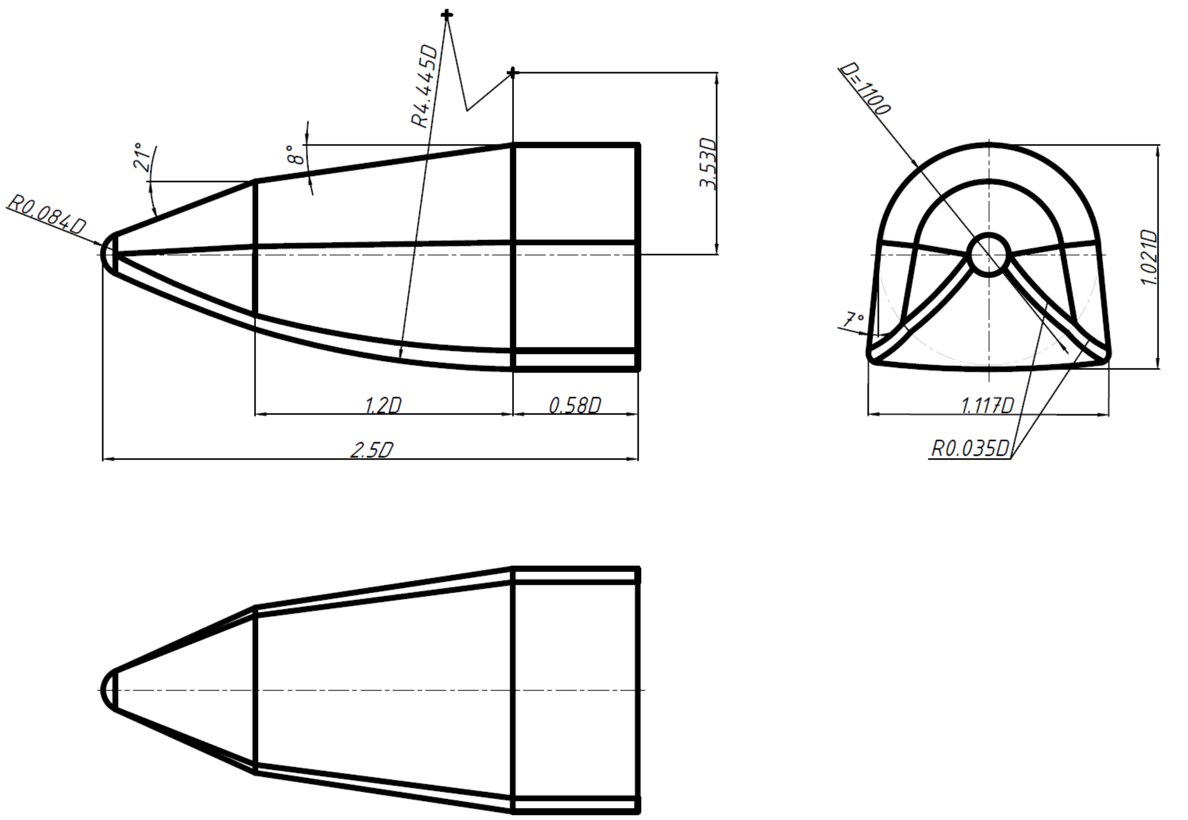


FIGURE 2. Aerodynamic form of the “lifting body” type of a lander, D=1100 mm.

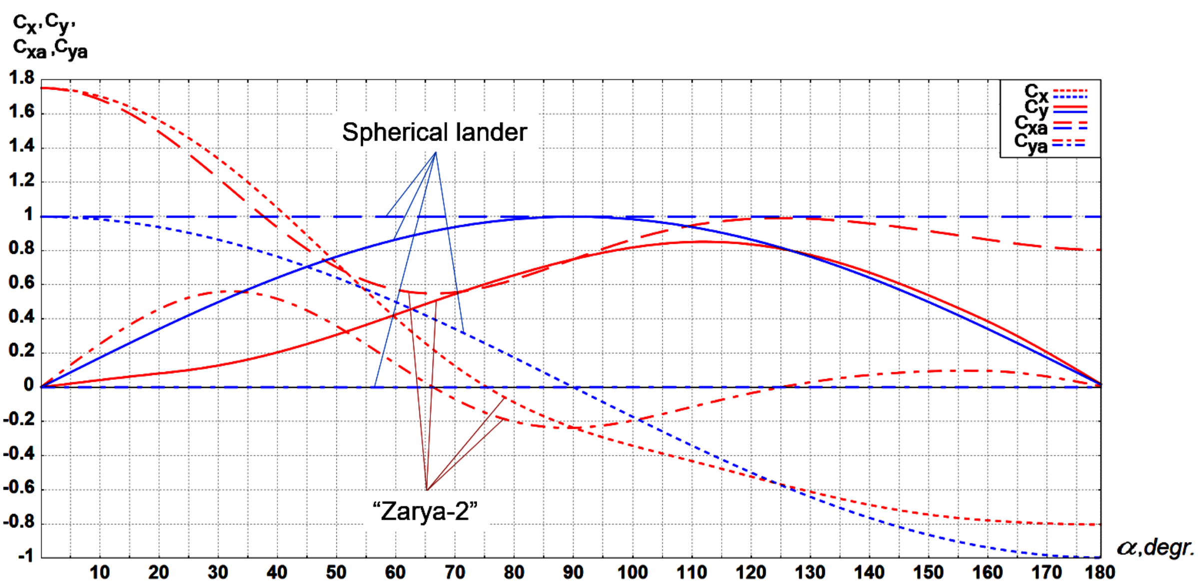


FIGURE 3. Aerodynamic coefficients for the form based on “Vega” (spherical lander, ballistic type) and “Zarya-2” (“gliding descent” type) landers

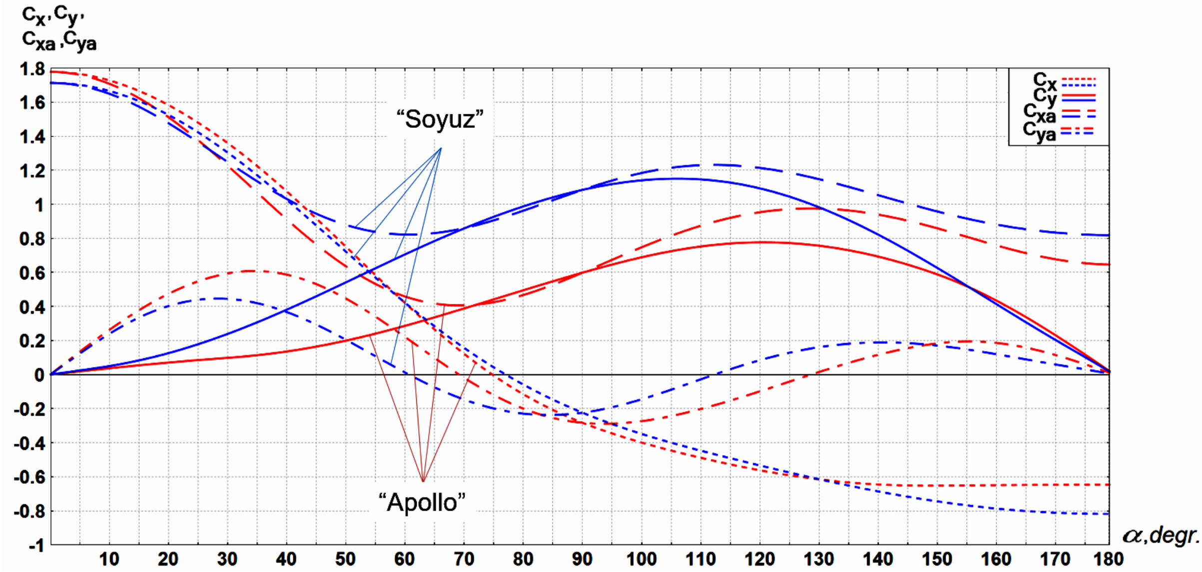


FIGURE 4. Aerodynamic coefficients for the form based on "Soyuz" ("gliding descent" type) and "Apollo" ("gliding descent" type) landers

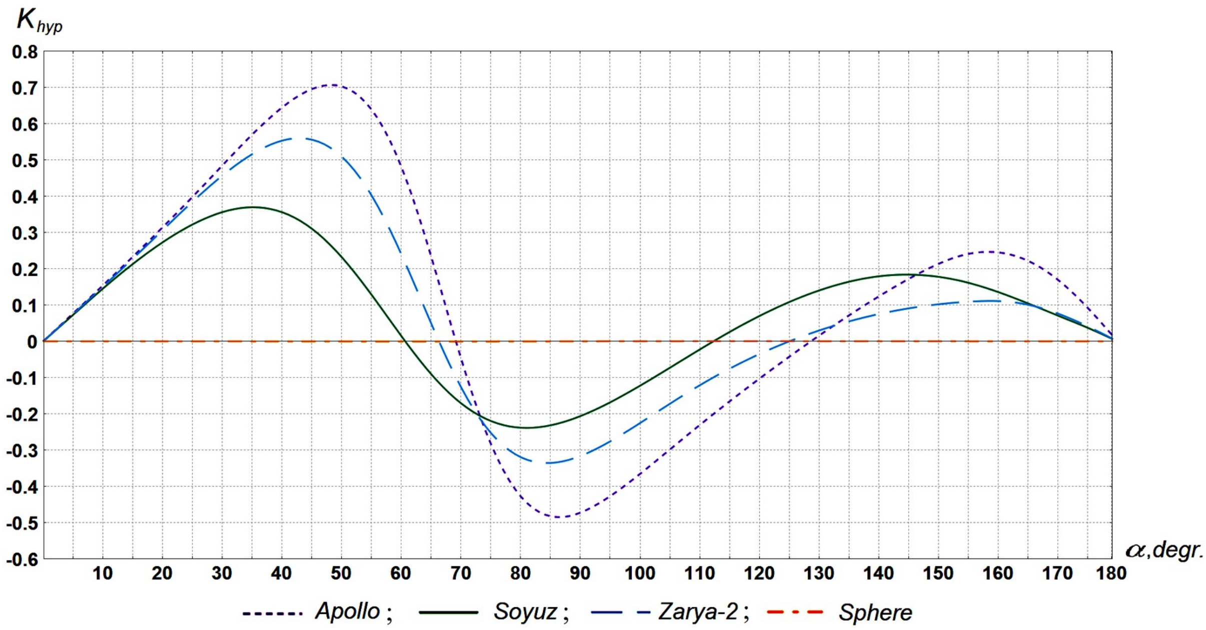
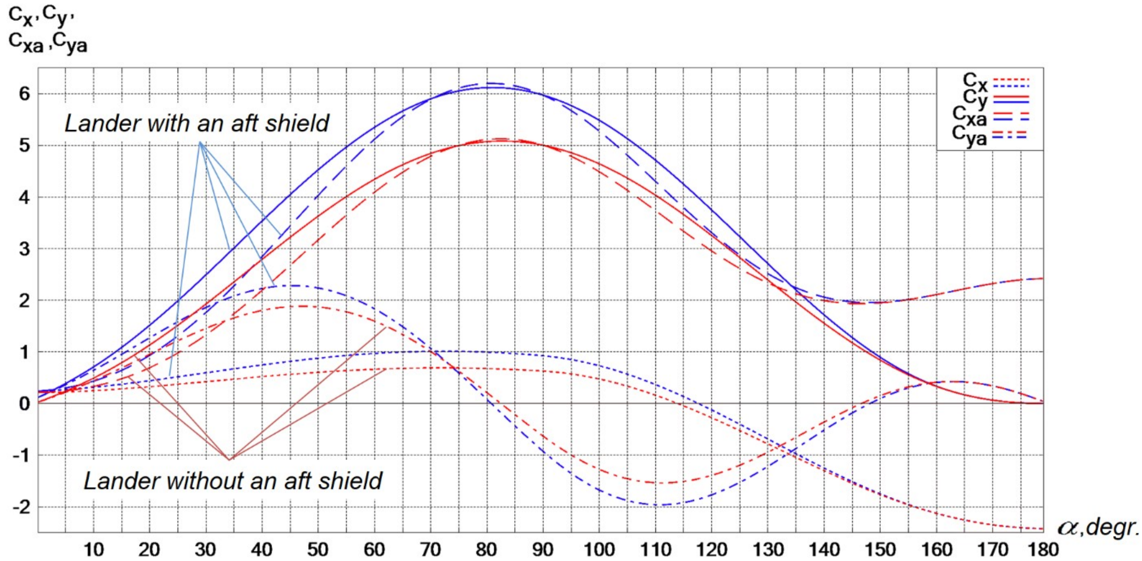
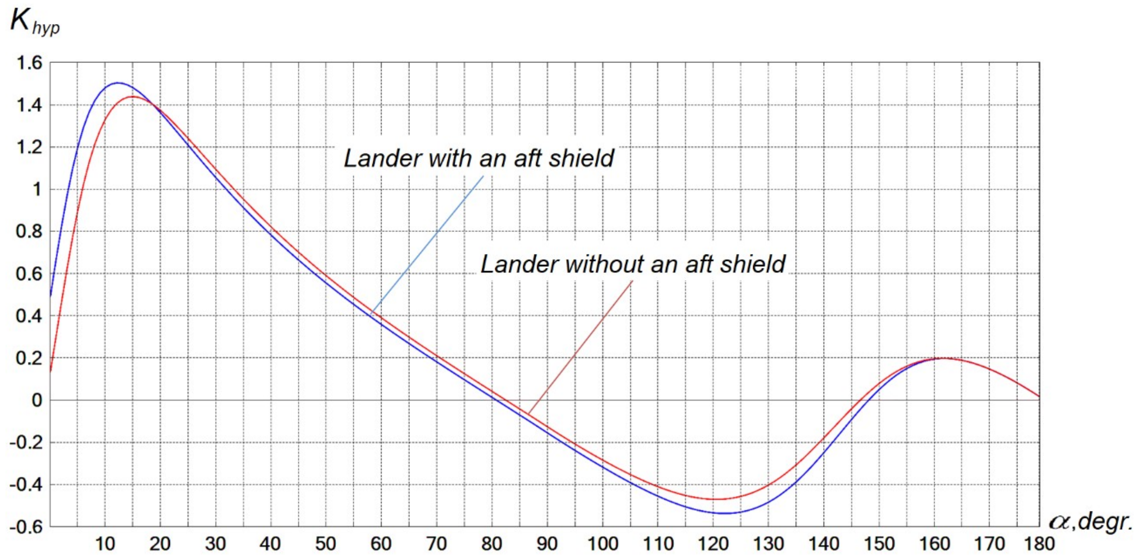


FIGURE 5. Aerodynamic lift-to-drag ratio for the form based on "Vega" (spherical lander, ballistic type), "Zarya-2" ("gliding descent" type), "Soyuz" ("gliding descent" type) and "Apollo" ("gliding descent" type) landers



a



б

FIGURE 6. Aerodynamic characteristics (a) and aerodynamic lift-to-drag ratio (b) for the "lifting body" type of a lander with and without an aft shield [19]

After calculating the aerodynamic characteristics of the lander in the given range of angles of attack, the coordinates of the center of pressure at the selected angle of attack is determined (See Figure 7), and a diagram of the aerodynamic forces is presented (See Figure 8).

Figure 7 shows the coordinates of the center of pressure for "Soyuz", "Apollo" and "Zarya-2" types of a lander presented in Figure 1. The issue of ensuring the stability for the "lifting body" type of a lander is presented in paper [19]

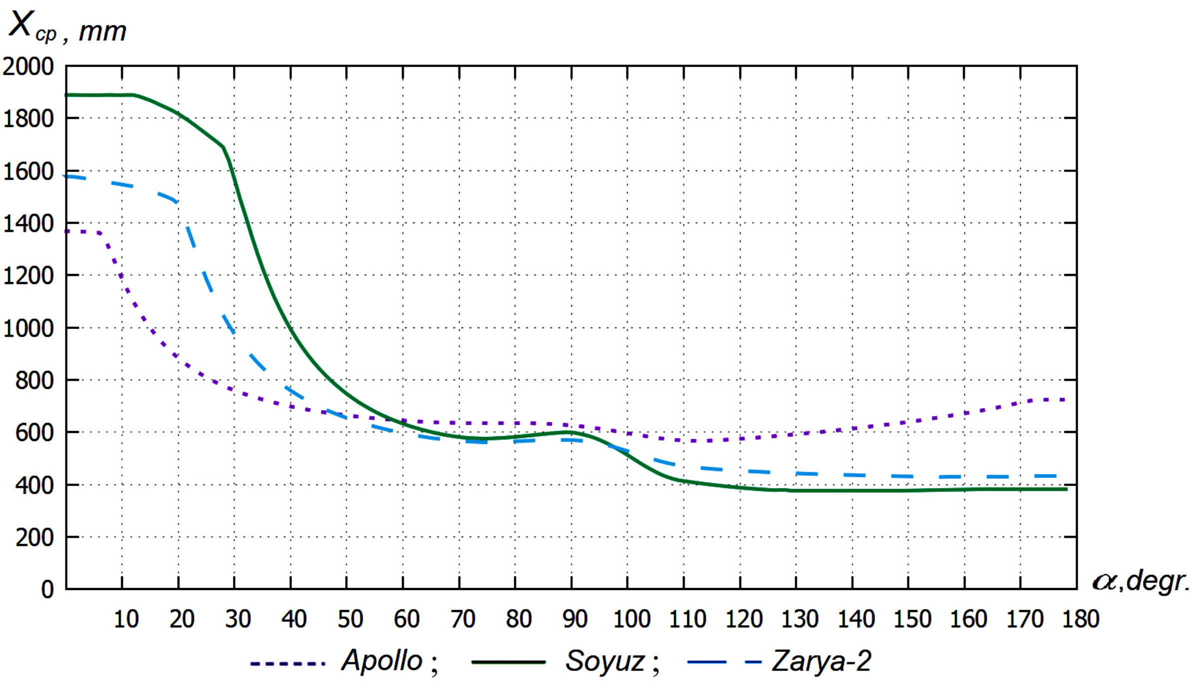


FIGURE 7. Center of aerodynamic pressure for "Soyuz" ("gliding descent" type), "Apollo" ("gliding descent" type) and "Zarya-2" ("gliding descent" type) landers

The center of mass of the lander should be on the line of the resultant aerodynamic forces for providing the stability of the lander during the descent at a given angle of attack, which is called trimmed angle of attack and is determined by the selected value of aerodynamic quality. For some types of a lander, the main condition may be the stability in the entire range of angles of attack, which implies the location of the center of mass behind the center of pressure is minimal.

Figure 8 shows that static stability of the lander is ensured by positioning the center of mass on the line of action of the total aerodynamic force C_r that is offset from the center of pressure in the direction opposite to the force vector. For the stability of the lander, it is necessary to provide the coordinates of the center of mass with some margin relative to the possible achievement of the minimum center of pressure according to the calculated data:

$$X_{cm} = X_{cp\,min} - \Delta X_{cp};\ Y_{cm} = (X_{cp} - X_{cm}) \cdot \mathrm{tg}\,\psi,\ \ \Delta X_{cp} = L/100,$$

$$\psi = arctg\left(\frac{C_y(\alpha_T)}{C_x(\alpha_T)}\right)$$

- angle between the longitudinal axis of the lander and the resulting aerodynamic force for the trimmed angle of attack

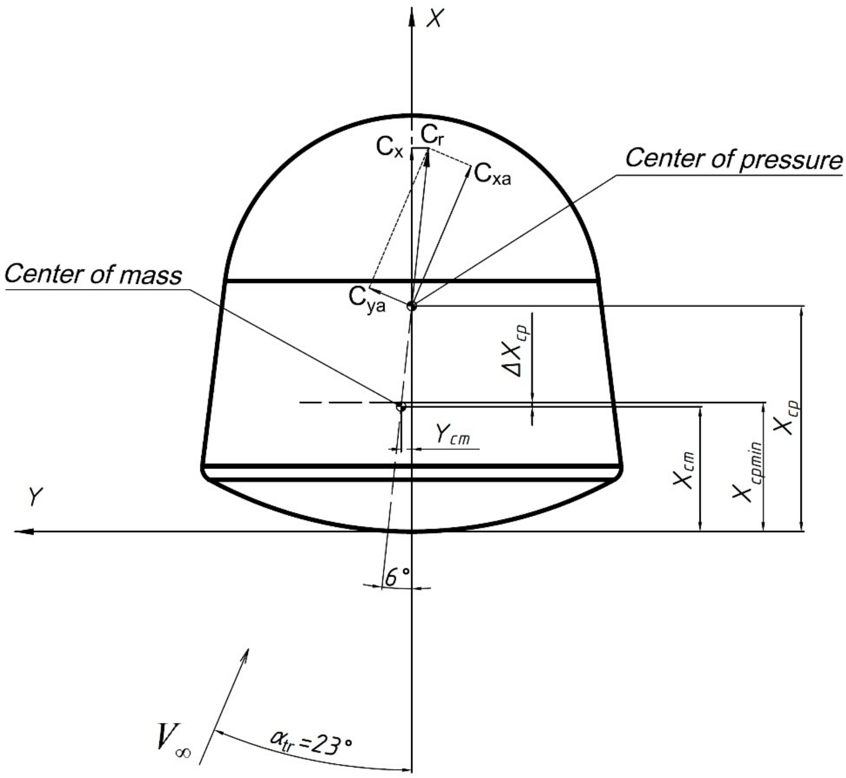


FIGURE 8. Diagram of aerodynamic forces on the example of "Soyuz" lander type

The calculation results for landers of "Soyuz", "Apollo", "Zarya-2" and the "lifting body" type of a lander are presented in Table 2.

TABLE 2. Main parameters for various types of a lander

Parameter	**Index**	**"Soyuz"**	**"Apollo"**	**"Zarya-2"**	**"Lifting body" (with an aft shield)[19,20]**
Diameter	*D (m)*	1.560	1.800	1.800	1.100
Height (length)	*L (m)*	1.540	1.250	1.340	2.750 (3.350)
Elongation	$\lambda = L/D$	0.987	0.694	0.74	2.5 (3.045)
Lift-to-drag ratio for hypersonic velocity range	K_{hyp}	0.3	0.5	0.5	1.4
Trimmed angle of attack (for the selected lift-to-drag ratio)	α_{tr}	23°	31°	34°	18°
Total surface area	$S_{\Sigma}\left(m^2\right)$	8.08	8.506	9.38	10.91
Center of gravity of surface	$X_T^S\left(m\right)$	0.669	0.544	0.619	1.794
Total volume	$V_{\Sigma}\left(m^3\right)$	2	1.95	2.1	2
Center of gravity of volume	$X_T^V\left(m\right)$	0.710	0.560	0.613	1.801
Volume efficiency (fill factor)	K_{fill}	0.953	0.887	0.847	0.7
Coordinate of the center of mass for X axis	$X_{cm}\left(m\right)$	0.463	0.562	0.613	1.803

Coordinate of the center of mass for Y axis	$Y_{cm}(m)$	0.040	0.070	0.032	-0.062
Coordinate of the center of pressure for X axis	$X_{cp}(m)$	0.835	1.490	0.865	1.916
Coordinate of the center of pressure for Y axis	$Y_{cp}(m)$	0	0	0	0.330

When designing a lander, an important parameter is lift-to-drag ratio for hypersonic velocity range, which affects the overloads acting on the lander and the available lateral maneuver during the descent in the atmosphere. As Figures 5 and 6 shows the ballistic types of a lander have zero lift-to-drag ratio and, therfore, do not have the ability to maneuver during the descent, segmental-conical forms of the “gliding descent” type of a lander have some lift-to-drag ratio, but no more than 0.7 for the entire attack angle range from 0 to 180 degrees. However, ensuring a required lift-to-drag ratio means that the lander mass increases and its structure becomes more complex. A trade-off solution would be to use landers of the “lifting body” type. The complication of the structure of such landers is permissible, and they have a lift-to-drag ratio sufficient for solving the existing maneuvering tasks in the Venus atmosphere. Lift-to-drag ratio for this type of a lander can be up to 1.5.

CONCLUSION

This paper discusses several alternatives to the traditionally used ballistic type of a lander on the Venus surface, as well as a comparative analysis of these landers by using operational design assessment of the aerodynamic forms of the landers.

As a result of the analysis, it is shown that the “lifting body” type of a lander has a higher lift-to-drag ratio and, therefore, can perform much more significant degree of maneuvering in comparison with the “gliding descent” type of a lander, which means that it can reach almost any landing site on the Venus surface, which ensures reaching the planned landing area most attractive for research. Moreover, compared to the ballistic type of a lander using the “lifting body” type of a lander results in reducing the overload for ensuring the integrity of the equipment during the descent in the atmosphere of the planet and reducing aerodynamic heat fluxes due to the small radius of the nose part of such lander.

Based on the foregoing, the “lifting body” type of a lander is proposed as perspective aerodynamic form of a lander for further studying as an alternative perspective form of the lander on the Venus surface.

REFERENCES

1. Abdrakhimov A.M., Geochemical comparison of volcanic rocks from terrestrial intraplate oceanic hot spots with Venusian surface material. *Geochem. Int.*, 2005, vol. 43, no. 8, pp. 732-747.
2. Limaye S.S., Kossin J.P., Rozoff C., Piccioni G., Titov D.V. and Markiewicz W.J. Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes. *Geophys. Res. Lett.*, 2009, vol. 36, no. 4, L04204, http://dx.doi.org/10.1029/2008GL036093.
3. Marov M.Y., Hantress U.T. (2013) Soviet robots in the solar system Technology and discoveries. Moscow: PHYSMATLIT, 612 p.
4. Vorontsov, V. A., Karchaev, Kh. J., Martynov, M. B., & Primakov, P. V. (2016). Venus exploration program and international cooperation. Trudy MAI, (86), 15.
5. Pioneer Venus Program Page // NASA's Solar System Exploration. URL: https://web.archive.org/web/20080925191131/http://solarsystem.nasa.gov/missions/profile.cfm?MCode=Pioneer_Venus
6. Dunne, James A.; Burgess, Eric. The Voyage of Mariner 10: Mission to Venus and Mercury (NASA SP-424). National Aeronautics and Space Administration Scientific and Technical Information Office, Washington, D.C., 1978.
7. Magellan Mission to Venus. URL: https://www2.jpl.nasa.gov/magellan/.
8. Venus Climate Orbiter Akatsuki. URL: http://akatsuki.isas.jaxa.jp/en/
9. Venus Express mission. URL: http://www.esa.int/Enabling_Support/Operations/Venus_Express.
10. Phase II repot of the Venera-D Joint Science Definition Team. Available at: https://www.lpi.usra.edu/vexag/reports/Venera-DPhaseIIFinalReport.pdf (accessed January 31, 2019)
11. Report of the Venera-D Joint Science Definition Team. Available at: http://www.iki.rssi.ru/events/2017/venera_d.pdf (accessed January 20, 2017)

12. Ghail R.C. et. al. VenSAR on EnVision: Taking earth observation radar to Venus. *Int. J. App. Earth Obs. Geoin.*, 2018, vol. 64, pp. 365–376, https://doi.org/10.1016/j.jag.2017.02.008.
13. Venus Flagship Mission Study: Report of the Venus Science and Technology Definition Team. Available at: https://www.researchgate.net/publication/41626005_Venus_Flagship_Mission_Study_Report_of_the_Venus_Science_and_Technology_Definition_Team (accessed September 15, 2009).
14. Grey Hautaluoma, Joshua Handal. "NASA Selects Four Possible Missions to Study the Secrets of the Solar System". *NASA News*. Washington, D.C. 13 February 2020. URL: https://www.nasa.gov/press-release/nasa-selects-four-possible-missions-to-study-the-secrets-of-the-solar-system
15. Zasova L.V., Moroz V.I., Linkin V.M., Khatuntsev I.V., Mayorov B.C. The structure of the Venus atmosphere from the surface to 100 km. *Kosmocheskie issledovaniya —Space Research*, 2006, no. 44, pp. 381-400.
16. Limaye S.S. et al. The thermal structure of the Venus atmosphere: Intercomparison of Venus Express and ground based observations of vertical temperature and density profiles. Icarus, 2017, vol. 294, pp. 124–155, https://doi.org/10.1016/j.icarus.2017.04.020.
17. Ivanov M.A. and Head J.W. Global geological map of Venus. *Planet. Space Sci.*, 2011, vol. 59, pp. 1559-1600, doi:10.1016/j.pss.2011.07.008.
18. Venera-D Landing Sites selection and Cloud Layer Habitability Workshop. October 2-5, 2019. IKI, Moscow, Russia. URL: http://www.venera-d.cosmos.ru/index.php?id=workshop2019&L=2
19. A.V. Kosenkova. Investigation of the possibilities of aerodynamic forms of a lander capable of maneuverable descent in the Venus atmosphere / *AIP Conference Proceedings*, 2171, 160005 (2019); https://doi.org/10.1063/1.5133309
20. Kosenkova, A.V.; Minenko, V.E.; Bykovsky, S.B., and Yakushev, A.G., 2018, Investigation of aerodynamic characteristics of lander alternative forms to study Venus. *Inzhenernyi zhurnal: nauka i innovatsii—Engineering Journal: Science and Innovations*, no. 11. URL: http://engjournal.ru/eng/catalog/arse/ahtp/1826.html
21. Campbell G. (1965) Low-velocity aerodynamic investigation of spacecraft landing process. In Series: Gas dynamics of spacecraft. Moscow: Mir, p. 29–55.
22. Alen H. Dzh. (1965) Gas-dynamic problems of spacecraft (collection Gas dynamics of spacecraft). Moscow: Mir, 182 p.
23. Bolotin, V.A., Minenko, V.E., Reshetin, V.A., Skotnikov, A.P., Schukin, A.N. (1997) Russian Patent No. 2083448. Retrieved from https://findpatent.ru/patent/208/2083448.html
24. Lukashevich V.P., Afanasyev I.B. (2009) Space wings. Moscow, LLC "LenTa Stranstvii", 496 p.
25. Kalugin V.T., Mordvintsev G.G., Popov V.M. (2011) Simulation process of flow and control the aerodynamic characteristics of aircraft. Moscow, Publishing Bauman Moscow State Technical University, 527 p.
26. Arzhannikov, N.S., Sadekova G.S. (1983) Aerodynamics of aircraft. Moscow: Vysshaya Shkola, 359 p.
27. Lunev V.V. (1975) *Hypersonic aerodynamics.* Moscow, Mashinostroenie, 328 p.