Journal of Applied Mechanics and Technical Physics, Vol. 44, No. 2, pp. 187–192, 2003

INVESTIGATION OF AERODYNAMIC DRAG OF TWO BODIES IN TRANS- AND SUPERSONIC FLOWS

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UDC 533.6.013.12

Results of experimental investigations of trans- or supersonic flow around two bodies (cone–disk or sphere–disk) connected by a cylindrical rod along the axis of symmetry are presented. The special features of the flow are analyzed. It is found that the dependence of the drag coefficient C_x of a pair of bodies on the Mach number within the range $0.6 \leqslant M \leqslant 1.7$ is nonmonotonic. The reasons for the hysteresis in the dependences $C_x(M)$ for two bodies at the stages of flow acceleration and deceleration and discrete variation of the Mach number are clarified. The influence of cone angles and sizes of both bodies on the drag coefficient is estimated.

Key words: *trans- and supersonic flow, drag coefficient, hysteresis, cone–disk pair, discrete variation of the Mach number.*

Introduction. Investigation of trans- and supersonic flow around bodies is needed to solve many problems of aviation and space engineering, such as descent of space vehicles with braking devices in planetary atmospheres, flight control in these regimes, etc. Many papers have appeared lately, which deal with trans- and supersonic flows around two bodies. These papers describe the results of studying the flow structure between the bodies [1–6], laws of pressure and heat-flux distributions over the surface of the body located in the wake [7–11], aerodynamic drag of a pair of bodies [12, 13], flow oscillations in the separation region [14, 15], etc. A classification of nonuniform (wake-like) supersonic flow around bodies is given in [16]. In the same paper, the influence of the degree of nonuniformity of the incoming flow on the flow pattern is analyzed and calculated and measured dynamic and thermal parameters for two differently shaped bodies not connected with each other are presented.

If the bodies are connected by thin rods, the flow pattern becomes different [17]. It is shown in [17] that, to obtain the upper estimates of the drag and heat-flux coefficients on the surface of the second (rear) body connected to the first (front) body, one can use the maximum values of these quantities on the rear body in the case the bodies are not connected [16]. It should be noted that the flow regimes around two bodies, depending on the Mach and Reynolds numbers, geometry of the bodies, and type of their connection, have not been adequately studied.

The study of deceleration of various pairs of bodies at transonic flow velocities is a complicated problem of computational and experimental aerodynamics. Its complexity rests on the fact that the system of two bodies is multiparametric; in addition, separated flows of various types can emerge, depending on the distance between the bodies [16]. The laws of reconstruction of the separated flow in the transition from the subsonic to supersonic flow around two bodies have been poorly studied. Experimental data for two bodies in the range of transonic velocities were obtained in [12, 13]. Belov et al. [12] presented results of an experimental study of the flow around a system consisting of a cone (cylinder) and a disk connected by a rod. The experiments were performed in a ballistic facility in the ranges of Mach and Reynolds numbers $1.2 \leqslant \mathrm{M} \leqslant 2.1$ and $4 \cdot 10^5 \leqslant \mathrm{Re} \leqslant 10^6$. The Reynolds number was based on the free-stream parameters, flight velocity of the model, and disk diameter D. The character of variation of the flow pattern around the pair of bodies was found, and the dependence of the drag coefficient C_x on the Mach number was obtained. It was found that the change in C_x is strongly nonmonotonic in a rather narrow range of Mach numbers. In [13], the flow around cylinder–disk models was studied in a wind tunnel with an open test section

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0021-8944/03/4402-0187 $25.00

TABLE 1

Body shape	Model number	d (D), mm	h, mm	θ, deg
Cone	1	14.8	15.0	26.2
	2	15.0	20.0	20.6
	3	15.0	25.0	16.7
	4	20.0	15.0	33.7
	5	20.0	20.0	26.6
	6	20.0	25.0	21.8
Cylinder	7	10.0	10.0	—
Sphere	8	10.3	—	—
Disk	I	20.0	5.0	—
	II	29.8	5.0	—

within the ranges $0.5 \leqslant \mathrm{M} \leqslant 1.7$ and $10^5 \leqslant \mathrm{Re} < 1.5 \cdot 10^6$ in the case of flow acceleration and deceleration in the wind tunnel and in the case of discrete variation of the Mach number. The dependence $C_x(\mathrm{M})$ was analyzed in the case of variation of the connecting rod length. The specific features of transition of the transonic flow structure into supersonic were described. For $\mathrm{M} = 1.7$, dependences of the drag coefficient of the model on the drag coefficient of the front body were obtained for flow schemes where separation occurred from the front body or from the rod.

The present work is a continuation of [12, 13].

1. Statement of Experiments. The cone–disk models were tested in an SVS-1 blowdown wind tunnel with an open test section, equipped by a contoured axisymmetric nozzle and perforated (50%) outlet. The Mach number in the test section was controlled by maintaining a certain pressure in the plenum chamber by means of throttling. The Mach and Reynolds numbers were varied within the ranges $0.6 \leqslant \mathrm{M} \leqslant 1.7$ and $10^5 < \mathrm{Re} < 1.5 \cdot 10^6$. The sizes of the sharp cones (first body) and disks (second body) are listed in Table 1 (d is the cone diameter, D is the disk diameter, h is the cone height or disk thickness, and θ is the cone angle). The bodies were mounted on stings of different length, which were fixed to a one-component balance. Two numbers were used to designate the model. In addition, each model was characterized by a parameter l, which was the ratio of the connecting rod length l_0 to the disk diameter D. The diameter of the rod connecting the bodies was 5 mm.

In usual tests, wind-tunnel starting was performed with a prescribed flow regime. The pressure in the plenum chamber was measured by a group manometer. The pipeline from the plenum chamber to the manometer gauge was a copper tube 3.5–4.0 m long with an inner diameter of 0.003 m. The drag force acting on the models was measured by a strain-gauge balance designed for steady tests and providing good reproducibility of results. The standard method used in the SVS-1 wind tunnel, however, is not suitable for tests with flow acceleration and deceleration. Therefore, two modifications were made in the test technique. First, a one-component balance was designed and fabricated for drag measurements (the prototype was the aerodynamic balance used in shock tubes). The new balance allowed an almost instantaneous (during 0.5 msec) recording of the drag force upon smooth variation of flow parameters in the wind tunnel. Second, an infrared detector was located in one of the technological orifices in the plenum chamber for pressure measurements. The readings of this detector via a voltmeter were recorded onto the oscillogram on which the values of the aerodynamic force were also registered. The distance from the model to the nozzle throat was less than 1.5 m. The time shift between the recording of the aerodynamic force and pressure in the plenum chamber onto the oscillogram was less than 7 msec, i.e., the measurements can be assumed to be almost simultaneous.

As was noted above, the Mach number in the tests was varied either continuously at the stages of flow acceleration and deceleration or discretely. Flow acceleration and deceleration lasted for 10–15 sec. The values of pressure P_{a} and temperature in the room where the tests were performed were recorded prior to each experiment. Based on these parameters and the pressure in the plenum chamber P_{pl}, we calculated the Mach number and dynamic pressure of the flow. According to metrological studies performed at the Central Aerohydrodynamic Institute, the static pressure P in the flow in the cross section where the model was located differed from the atmospheric pressure P_{a} by 1, 0.5, 1, and 3% for $\mathrm{M} = 1.1$, 1.2, 1.5, and 1.7, respectively. The nozzle with the perforated (50%) outlet for $\mathrm{M} > 1$ had some total-pressure losses, which did not exceed 0.25%. The difference between the true value of the flow Mach number in the test section obtained using the above factors and the Mach number calculated by the ratio $P_{\mathrm{pl}}/P_{\mathrm{a}}$ reached the maximum value for $\mathrm{M} = 1.5$–1.7, which did not exceed 1.3%. Flow deflection in the vertical and horizontal planes in the test section was less than 0.4°.

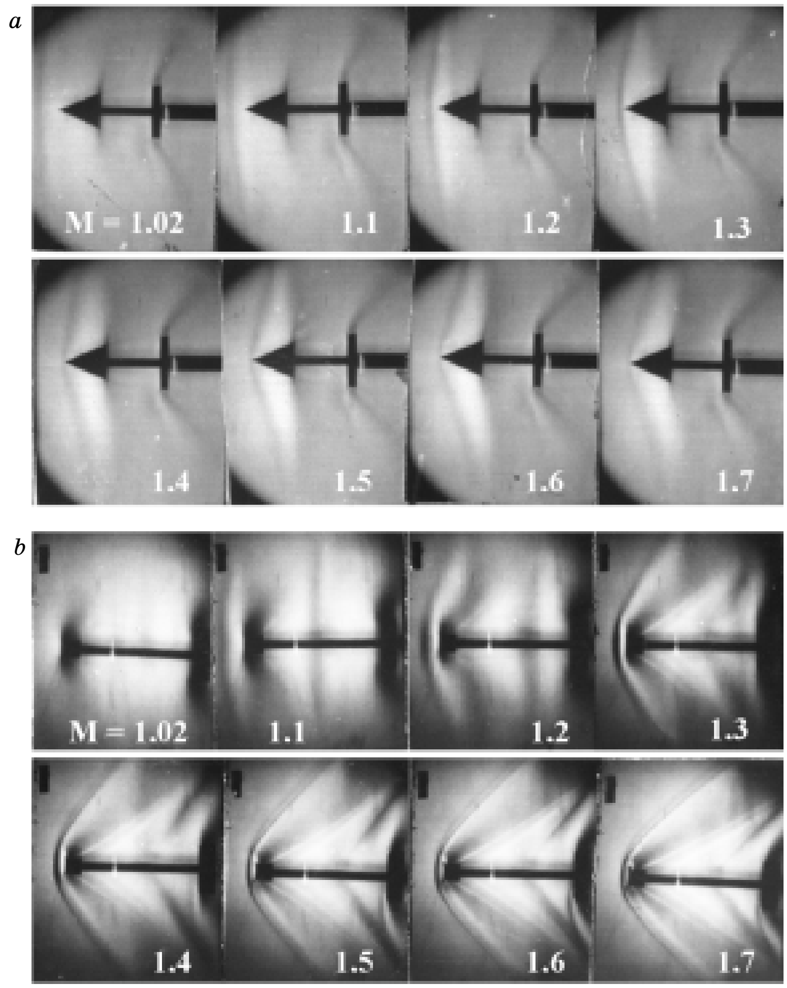

Fig. 1. Frames of the flow around the models upon flow acceleration (M = 1.02–1.7): (a) 2–I (cone–disk) model for $l = 1.5 < l^*$; (b) 7–II (cylinder–disk) model for $l = 2 > l^*$.

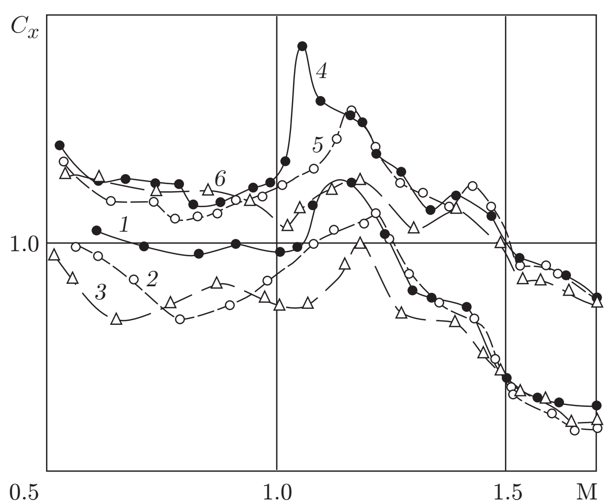

Fig. 2. Drag coefficient of the sphere–disk model versus the Mach number of the incoming flow at the stages of flow acceleration (1 and 4) and deceleration (2 and 5) and discrete variation of the Mach number (3 and 6): curves 1–3 refer to the 8–I model for $l = 1 < l^*$ and curves 4–6 refer to the 8–II model for $l = 2 > l^*$.

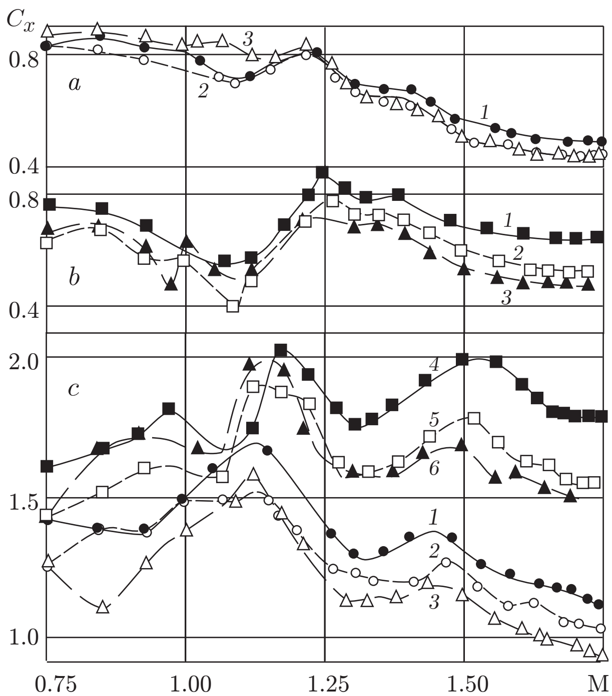

Fig. 3

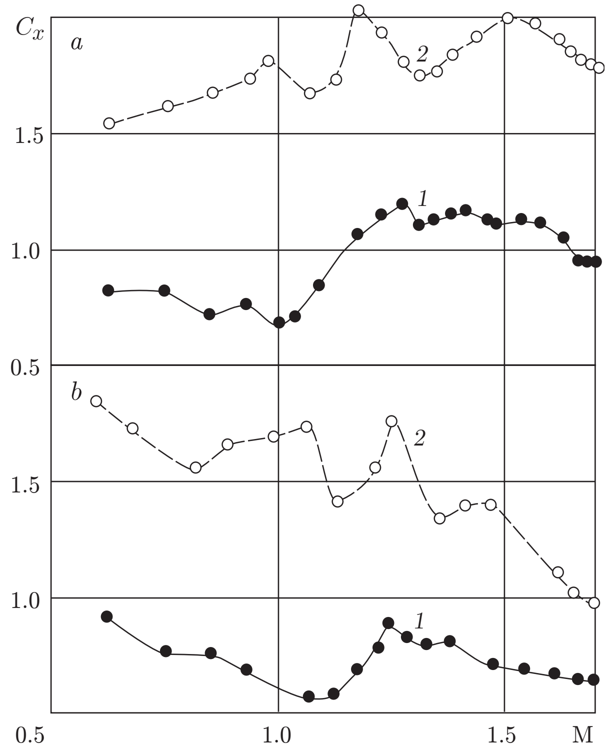

Fig. 4

Fig. 3. Drag coefficient of the cone–disk model versus the free-stream Mach number at the stage of flow acceleration: (a) $l = 1.5 < l^*$ for configurations 1–II (1), 2–II (2), and 3–II (3); (b) $l = 1.5 < l^*$ for configurations 4–II (1), 5–II (2), and 6–II (3); (c) $l = 4.5 > l^*$ for configurations 1–I (1), 2–I (2), 3–I (3), 4–I (4), 5–I (5), and 6–I (6).

Fig. 4. Drag coefficient of the cone–disk model versus the free-stream Mach number at the stage of flow acceleration: (a) configuration 4–II for $l = 1.5 < l^*$ (1) and $l = 2.5 > l^*$ (2); (b) configuration 4–I for $l = 2.25 < l^*$ (1) and $l = 4.5 > l^*$ (2).

The aerodynamic force acting on the model during the tests was measured by the balance within 1%. The disk area was used to calculate the coefficient C_x of the model. Schlieren pictures of the flow around the model were taken. The filming velocity was 24 frames per second.

2. Test Results. Figure 1 shows the typical sequence of frames of the flow pattern. The dependences C_x(M) at the stages of flow acceleration and deceleration and discrete variation of the Mach number are plotted in Fig. 2. A comparison of the data in Figs. 1 and 2 shows that, at the stage of flow acceleration, attachment of the shock wave to the cone and formation of a supersonic separation region between the cone and disk [$l < l^*$ (see Fig. 1a)] are accompanied by a local increase in the coefficient C_x within a rather narrow range of Mach numbers [for the sphere–disk model, such an increase in C_x is observed for M = 1.15 (curve 1 in Fig. 2)]. In Figs. 2–4, $l^* = l_0^*/D$, where l_0^* is the critical distance between the bodies at which flow separation is shifted from the cone edge to the rod. For $l > l^*$, the dependence C_x(M) has two local peaks. The first peak corresponds to bending of the bow shock wave ahead of the first body (or attachment to the apex if the first body was a cone) and displacement of the local supersonic region toward the disk. The second peak corresponds to the formation of a supersonic separation region ahead of the disk (see Fig. 1b). For the sphere–disk model, the local maxima of C_x were registered for M ≈ 1.06 and $\approx$1.4 (curve 4 in Fig. 2).

The measured results of the drag force of two bodies in standard wind-tunnel tests with an aerodynamic balance for fixed Mach numbers were well reproduced, as well as the results of the drag force of the model measured by the new balance. At the same time, an analysis of the dependences C_x(M) in Fig. 2 shows that, under conditions of flow acceleration and deceleration in the wind tunnel, the maximum values of C_x and their position in the range $0.6 < \text{M} < 1.45$ vary and differ from the values obtained by discrete variation of the Mach number, which indicates the existence of a hysteresis in the dependence C_x(M). Apparently, this can be attributed to flow unsteadiness near the pair of bodies in flow regimes examined. Quantitative information on the influence of unsteadiness can be obtained only after similar tests with registration of flow-regime variation in the wind tunnel.

Since the dependences C_x(M) in Fig. 2 are in qualitative agreement for $l < l^*$ and $l > l^*$ for different methods of varying the wind-tunnel operation regime, the effect of the cone size, distance between the bodies, and disk diameter on the coefficient C_x was further considered in the regime of flow acceleration.

Figure 3 shows the dependences C_x(M) for cone–disk models at the stage of flow acceleration. An analysis of these dependences shows that the coefficient C_x has one local maximum at M = 1.20–1.25 (Fig. 3a and b) for conical front bodies for M > 1, as in the case of a blunted front body (curves 1 and 4 in Fig. 2) for $l < l^*$ and two local maxima at M = 1.13–1.17 and M = 1.46–1.52 (Fig. 3c) for $l > l^*$. For M > 1.3, the values of C_x increase with increasing cone drag in the free stream (see Fig. 3b and c).

We consider the influence of the length of the connecting rod between the bodies and disk diameter on the dependence C_x(M) for the cone–disk model with a fixed geometry of the front body.

Figure 4 shows the dependences C_x(M) for the cone–disk model at the stage of flow acceleration. Independent of the disk diameter, flow reconstruction at $l < l^*$ (curves 1) and $l > l^*$ (curves 2) is accompanied by an increase in the coefficient C_x within the entire range of Mach numbers under study, including subsonic flow. In this case, the increase in the dependence C_x(M) is caused by the fact that the disk leaves the aerodynamic shadow of the front cone as the rod length increases, which leads to an increases in disk drag.

Note also that one more local maximum of C_x appears in the case $l > l^*$ (curves 2 in Fig. 4) at M = 0.97–1.05, which is caused by the increase in base drag behind the cone [18].

The values of the coefficient C_x for $0.7 \leqslant \mathrm{M} < 1$ in the case of $l < l^*$ (curves 1 in Fig. 4) and for $0.75 \leqslant \mathrm{M} < 1.1$ in the case of $l > l^*$ (curves 2 in Fig. 4) almost coincide. However, in supersonic flows with M > 1 ($l < l^*$) and M > 1.1 ($l > l^*$), the value of C_x for the 4–I model is higher than for the 4–II model. Nevertheless, within the entire range of Mach numbers examined, the drag force acting on the 4–II model is greater than the drag force acting on model 4–I, since the ratio of disk areas is 2.25.

Conclusions. The experiments performed helped in understanding the flow pattern around a pair of bodies and in determining the dependence C_x(M) in the range of Mach numbers 0.6 < M < 1.7. The reasons for the hysteresis of the dependences C_x(M) at the stages of flow acceleration and deceleration and discrete variation of the Mach number are elucidated.

This work was partly supported by the Russian Foundation for Fundamental Research (Grant Nos. 01-01-00050 and 00-15-96030).

REFERENCES

1. A. F. Charwat, J. N. Roos, F. G. Dewey, and J. A. Hitz, "An investigation of separated flows. Part 1. The pressure field," *J. Aerospace Sci.*, **28**, No. 6, 457–470 (1961).
2. B. Dayman (Jr.) and D. W. Kurtz, "Forebody effects on drogue drag in supersonic flow," AIAA Paper No. 68-8 (1968).
3. Yu. L. Karpov, Yu. P. Semenkevich, and A. Ya. Cherkez, "Calculation of the separated flow between two bodies," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 3, 88–94 (1968).
4. V. N. Kudryavtsev, A. Ya. Cherkez, and V. A. Shilov, "Investigation of supersonic flow around two separating bodies," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 2, 91–99 (1969).
5. V. S. Khlebnikov, "Supersonic flow pattern around a pair of bodies and flow reconstruction between the bodies," *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 1, 158–165 (1994).
6. P. G. Tsyganov, "Effect of the drag of the front body on flow reconstruction between two bodies, one of them being located in the supersonic wake of the other," *Tr. TsAGI*, No. 2494, 3–12 (1991).
7. Yu. P. Golovachev and N. V. Leont'eva, "Numerical investigation of the flow around a blunted body located in a supersonic wake," Preprint No. 918, Ioffe Physicotech. Inst., Leningrad (1984).
8. V. S. Khlebnikov, "Supersonic axisymmetric gas flow around a pair of bodies," *Uch. Zap. TsAGI*, **9**, No. 6, 108–114 (1978).
9. I. A. Belov, A. N. Mikhalev, I. M. Dement'ev, et al., "Modeling of a supersonic flow around bodies of revolution with a front separation region," Preprint No. 1033, Ioffe Physicotechn. Inst., Leningrad (1986).

10. I. G. Eremeitsev, N. N. Pilyugin, V. S. Khlebnikov, and S. A. Yunitskii, *Investigation of Aerodynamic Characteristics and Heat Transfer of Bodies in Nonuniform Supersonic Gas Flows* [in Russian], Izd. Mosk. Univ., Moscow (1988).
11. N. N. Pilyugin and V. S. Khlebnikov, "Typical features of flow upstream of the body located in a supersonic near wake," *Teplofiz. Vys. Temp.*, **37**, No. 2, 268–273 (1999).
12. V. E. Belov, V. S. Khlebnikov, and P. G. Tsyganov, "Drag of a pair of bodies at supersonic flight velocities," *Uch. Zap. TsAGI*, **16**, No. 3, 114–117 (1985).
13. V. S. Khlebnikov, "Aerodynamic drag of a pair of bodies in trans- and supersonic flow," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 3, 152–156 (1990).
14. V. I. Zapryagaev, "Pulsations in the separation zone of a free cavern at a supersonic stream velocity," *J. Appl. Mech. Tech. Phys.*, **26**, No. 6, 802–808 (1985).
15. V. S. Khlebnikov, "Experimental study of supersonic three-dimensional separated flow between a plane and a sphere," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 5, 166–170 (1987).
16. N. N. Pilyugin, R. F. Talipov, and V. S. Khlebnikov, "Nonuniform supersonic wake-like flow around bodies," *Teplofiz. Vys. Temp.*, **34**, No. 5, 780–795 (1996).
17. N. N. Pilyugin and V. S. Khlebnikov, "Aerothermodynamic characteristics of the rear body in a supersonic flow," *Teplofiz. Vys. Temp.*, **39**, No. 4, 620–628 (2001).
18. Paul K. Chang, *Separation of Flows*, Pergamon Press, Oxford (1970).