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CALCULATING BODIES IN SUPERSONIC FLOW AT GREAT ANGLES OF ATTACK--ETC(U)

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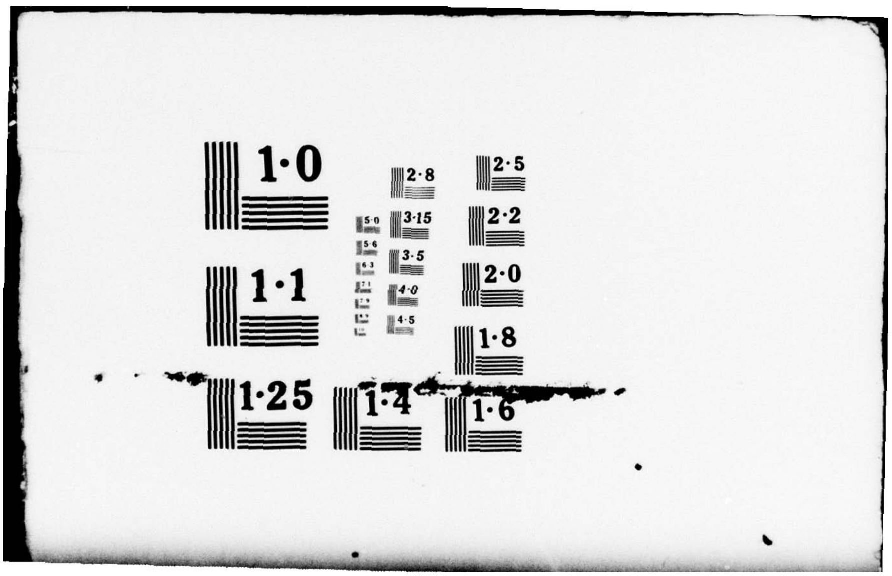
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FOREIGN TECHNOLOGY DIVISION

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by

Yu. N. D'yakonov, L. V. Pchelkina,
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EDITED TRANSLATION

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А а	*А а*	A, a	Р р	*Р р*	R, r
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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
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И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

CALCULATING BODIES IN SUPERSONIC FLOW AT GREAT ANGLES OF ATTACK

Yu. N. D'yakonov, L. V. Pchelkina, I. D. Sandomirskaya

In studying rather long blunt bodies in a flow at great angles of attack $\alpha \geqslant \beta$ (β is the angle of slope of the contour) using various numerical methods adapted for calculating smooth gas flows, a feature was discovered in the leeward region of the flow [1-3] which made it impossible without taking special measures to continue calculating for the quantity x greater than a certain critical length value $x_{кр}$ (generally depending on the parameters of the impinging flow and the geometry of the body). Analysis of existing results and, foremost, the nature of the distribution of the peripheral component of velocity vector w close to the surface of the body permits us to assume that this phenomenon is related to the development in the shadow region of the flow of a feature such as a shock wave resulting from the collision of supersonic flows directed toward one another at great angles.

The results of calculating flows near sharpened conical bodies at great angles of attack [4] also indicate the possibility of the development of such a peculiarity.

During experimental study of the flow past sharp cones and rather long blunt cones at great angles of attack under actual conditions in the presence of viscous forces on the shadow side of the body, developed separation zones are formed [5 and elsewhere]. It is interesting to note that in the peripheral direction the flow pattern greatly resembles a supersonic gas flow past a round cylinder. Specifically, the value of meridional angle ψ at which the separation zone is formed in the three-dimensional case is not in good agreement with corresponding results for the two-dimensional flow. Thus, in the first approximation we can assume that even the experimental results do not contradict the assumption of the development of a shock wave type of peculiarity when $\alpha \geqslant \beta$ on the leeward side of rather long bodies.

At great angles of attack the pressure on the attack side of the body is generally significantly greater than the pressure on the shadow side of the flow. Moreover, in the presence of develope separation zones, calculation for an ideal fluid in this region can differ markedly from the real values of the gas dynamic parameters because of the strong influence of viscous effects.

The situation may prove analogous to that which occurs in a supersonic flow past a sphere. Using inviscid gas equations we can calculate this flow up to the value of θ ~~ 160° (polar angle θ is reckoned from the critical point). However, when $\theta > \theta_{отр}$ ~~ 110-120° the obtained solution does not reflect the real flow pattern, since this entire region lies within the flow separation zone. Therefore, a practical solution to the problem of calculating bodies in a supersonic gas flow at great angles of attack might be the following.

Outside of the separation zone the flow is calculated using the model of an ideal gas, which, as we know, in this case describes the process very well. The distribution of pressure in the separation zone is assigned on the basis of experimental data and obtained calculation results for the smooth flow region. Since pressure in this zone is significantly lower than the pressure on the attack side of the flow and as analysis of calculation results shows, even a rather rough distribution of gas parameters in the separation region will not lead to great error in the values of the sum aerodynamic characteristics of blunt cones. Thus, we can assume that such a system will provide an accuracy in calculating the flow past bodies at great angles of attack which is sufficient from the practical standpoint.

In this study to calculate a three-dimensional steady gas flow in the supersonic range we used the grid method in the form discussed in [6]. Let us look at some modifications of the method which must be made in order to perform a calculation according to the system described above (symbols of [6] used here).

Let us assume that we have a uniform supersonic flow against an axisymmetrical body at angle of attack α and (x, y, ψ) a cylindrical coordinate system bound to the body; the x axis coincides with the axis of symmetry. Meridional angle ψ is reckoned from the plane of the angle of attack α, while the value $\psi=0^{\circ}$ is assigned to the attack side. In view of the symmetry with respect to variable it is sufficient to examine the gas flow in the range $0^{\circ}\leqslant\psi\leqslant180^{\circ}$.

Let us introduce into the region where we seek the solution $x > x_0$, $0 \leqslant \xi \leqslant 1$, $0 \leqslant \psi \leqslant \pi$, a grid with nodes $(\tau n, mh_1, lh_2)$, where

$$\tau = \Delta x;\ h_1 = \Delta\xi;\ h_2 = \Delta\psi = \text{const};\ n = n_0,\ n_0 + 1,\ n_0 + 2,\ \ldots;$$

$$m = 0, 1, 2, \ldots, M;\ l = 0, 1, 2, \ldots, L;\ h_1M = 1;\ h_2L = \pi.$$

The system of difference equations is written for the point

$$\left[\left(n+\frac{1}{2}\right)\tau;\ \left(m+\frac{1}{2}\right)h_1;\ lh_2\right].$$

For approximating derivatives with respect to ψ we use difference relationships analogous to the formulas of (6) from [6]:

$$\left(\frac{\partial X}{\partial \psi}\right)^{n+\frac{1}{2}}_{m+\frac{1}{2},l} = \frac{1}{4h_2}\left[\alpha\left(X^{n+1}_{m+1,l+1} - X^{n+1}_{m+1,l-1} + X^{n+1}_{m,l+1} - X^{n+1}_{m,l-1}\right) + \right.$$
$$\left. + \beta\left(X^{n}_{m+1,l+1} - X^{n}_{m+1,l-1} + X^{n}_{m,l+1} - X^{n}_{m,l-1}\right)\right], \quad (1)$$

where $X = [u, v, w, \pi, \mathcal{E}]$ represents the vector column of unknown functions, u, v, w - projections of the velocity vector onto axis x, y, and ψ, respectively; $\alpha \geqslant \beta \geqslant 0$, $\alpha + \beta = 1$.

For simplicity let us assume that the separation region coincides with one of the beams $\psi_l = lh_2$ and $l \neq L$. Let us assume, for example, that this beam $l = L - 1$, and then it will be the last even beam. No matter how we write derivatives with respect to ψ, as long as we remain within the framework of the explicit iteration system for that variable, the main calculation algorithm remains virtually unchanged, although calculation of the right part of the difference equations will be done somewhat differently. For approximation of the derivatives with respect to ψ on this last beam $\psi_l = lh_2$ we might, for example, assume the following relationships:

$$\left(\frac{\partial X}{\partial \psi}\right)^{n+\frac{1}{2}}_{m+\frac{1}{2},\,l} = \frac{1}{2h_2}\,[\alpha\,(X^{n+1}_{m+1,\,l} - X^{n+1}_{m+1,\,l-1} + X^{n+1}_{m,\,l} - X^{n+1}_{m,\,l-1}) + \tag{2}$$

$$+ \beta\,(X^{n}_{m+1,\,l} - X^{n}_{m+1,\,l-1} + X^{n}_{m,\,l} - X^{n}_{m,\,l-1})],$$

$$\left(\frac{\partial X}{\partial \psi}\right)^{n+\frac{1}{2}}_{m+\frac{1}{2},\,l} = \frac{1}{4h_2}\,[\alpha\,(3X^{n+1}_{m+1,\,l} - 4X^{n+1}_{m+1,\,l-1} + X^{n+1}_{m+1,\,l-2} +$$

$$+ 3X^{n+1}_{m,\,l} - 4X^{n+1}_{m,\,l-1} + X^{n+1}_{m,\,l-2}) + \tag{3}$$

$$+ \beta\,(3X^{n}_{m+1,\,l} - 4X^{n}_{m+1,\,l-1} + X^{n}_{m+1,\,l-2} + 3X^{n}_{m,\,l} - 4X^{n}_{m,\,l-1} + X^{n}_{m,\,l-2})].$$

Formulas (2) and (3) are obtained by means of "unilateral" difference relationships, and when $\alpha = \beta$ and the number of iterations $Q \geqslant 2$, they assure the first and second order of accuracy, respectively. It is assumed that the gas flow in region $\psi > \psi_l$ has no effect on the purely gas dynamic region $\psi \leqslant \psi_l$, i.e., no additional conditions need be imposed on the last even beam.

Results from experiments on and calculations of a supersonic flow past bodies at great angles of attack in many cases confirm this assumption. Specifically, in [1, 3, 7 and elsewhere] it was discovered that at high values of meridional angle ψ on the shadow side of the flow the peripheral components of the velocity vector w can reach supersonic values.

If in the last even beam peripheral velocity everywhere is greater than the local speed of sound, then the proposed system is essentially based on the same ideas as the method developed in [4] for calculating two-dimensional steady gas flows near conical bodies at great angles of attack. In this case such a formulation of the problem is obviously correct. As indicated by the experienced gained from calculating and comparing results obtained by the proposed system and the standard method [6] (in the region where data can still be obtained using the standard difference system), this system can be successfully used even when the condition indicated above is destroyed. The explanation for this is as follows: although the peripheral velocity component on beam $\psi=\psi_1$ is also lower than the local speed of sound, for the studied flows it is comparable to it in magnitude. Therefore, little information is transmitted from the region $\psi>\psi_1$ to the region $\psi<\psi_1$, and it has virtually no effect on calculation when $\psi<\psi_1$.

The fact that we can determine the numerical solution (which corresponds to reality) in the region of the gas flow bounded by a certain line on which the velocity component which is normal to it is below the speed of sound, but comparable to it in magnitude (despite the fact that the formulation of the problem in this case becomes incorrect, strictly speaking), is also confirmed by the special methodological calculation conducted in [8]. Studied in this last work was the flow pattern which develops when a supersonic freely expanding stream strikes a surface. The characteristic feature of such a flow is the formation of an open narrow subsonic flow zone adjoining the shock wave in front of the obstacle. Let us note certain peculiarities in the flow past blunt bodies at high angles of attack. If we compare the data in Figs. 1-4, where we see the flow patterns for a blunt cone in an equilibrium air flow at number M_{∞} = 20, pressure p_{∞} = 0.001 atm phys. and temperature T_{∞} = 250°K, and the pressure distribution on the surface of the cone, we see a marked shortening in the region effected by the blunting as the angle of attack grows. When α = 30° (Fig. 4) at great distances from the leading edge, the nature of the pressure distribution on the body p_s with respect to the meridional angle ψ is in good agreement with corresponding results from [4] for sharp cones at great angles of attack.

The use of the system for the shadow side of the flow virtually eliminates the significant limitations on the length of a calculated body flying at a great angle of attack, which existed previously (for example, the standard method of calculating a flow past the same cone, even for α = 10°, not to mention greater angles, could only be done up to x ~~ 10).

Since on the attack side the flow, even at short distances from the blunt portion, becomes close to conical (with the exception of the thin vortex layer near the body), there develops a zone of drastic restructuring from the "almost clinical" flow to an entirely different type of flow, corresponding to the flow past the leading portion of a body. In the vicinity of this zone, in the field and on the shock wave, flow peculiarities of a different type may develop. To study them we must conduct calculations with a dense grid for coordinates ξ and ψ along with a thorough analysis of the flow in the compressed layer and the geometry of the shock wave.

Naturally the obtained results correspond to the actual flow pattern only in the gas dynamic region inside the separation zone. Based on the data of experiments in [5] for cones with a half-angle of $\beta \sim 10°$ at Mach numbers of $M_{\infty} = 6$ and great angles of attack the separation zone lies in the region of meridional angle values $\psi \geq 140°$.

The proposed calculation system can be easily extended to the case where the boundary of the separation zone is assigned in the form of a certain function (determined, let us say, from the results of experimental studies) or is found by the gasdynamic parameters obtained in the process of solving the problem. This is especially true if we consider the fact that, in view of the above discussion, it is not necessary to assign this boundary with a high degree of accuracy.

Further refinement of the formulation of the problem and obtained results requires that we conduct systematic calculational investigations and a thorough experimental study of the shape of the boundaries of the separation zone, distribution of gas parameters in this region, and the effect of bodies flying at great angles of attack, the parameters of the impinging flow, Re numbers, the nature of the gas flow in the boundary layer, etc. on the flow pattern on the shadow side.

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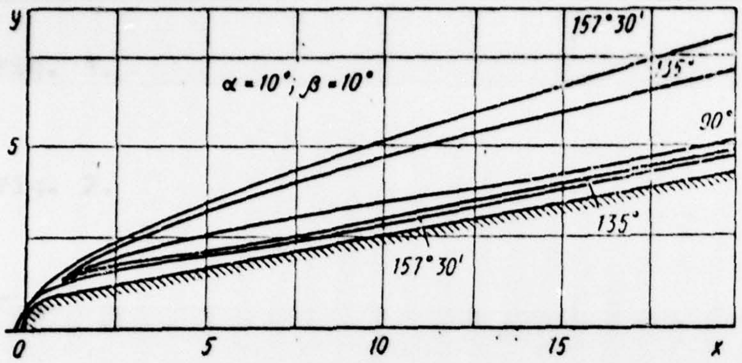

Fig. 1.

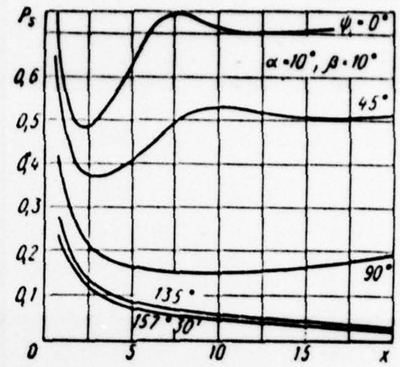

Fig. 2.

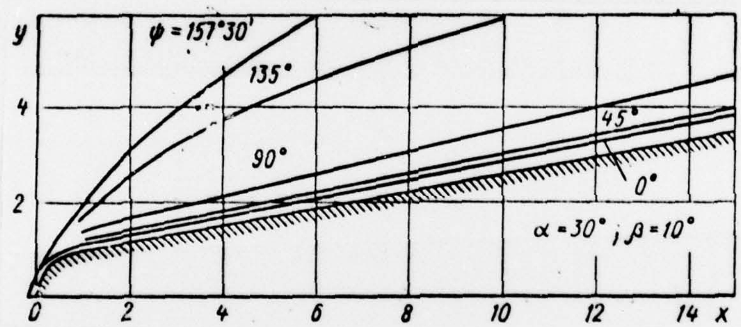

Fig. 3.

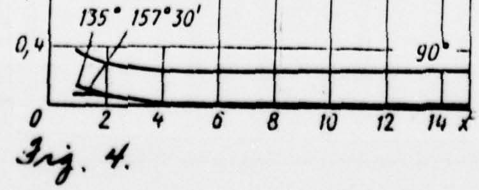

Fig. 4.

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