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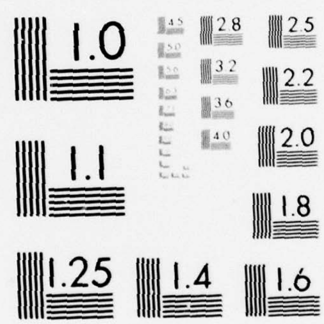

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EXPERIMENTAL STUDY OF THE MAGNUS EFFECT ON A FINNED BODY OF REVOLUTION OF GREAT ELONGATION AT A MACE NUMBER OF M = 4

By

N. M. Bychkov, B. L. Dubrovskiy, V. M. Kovalenko

FOREIGN TECHNOLOGY DIVISION

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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

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> 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

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EXPERIMENTAL STUDY OF THE MAGNUS EFFECT ON A FINNED BODY OF REVOLUTION OF GREAT ELONGATION AT A MACH NUMBER OF M = 4

N. M. Bychkov, B. L. Dubrovskiy, V. M. Kovalenko

During the flight of a rotating missile or rocket at an angle of attack aerodynamic forces arise which are directed along the normal to the plane of the angle of attack, i.e., the so-called Magnus effect is manifested. The presence of a lateral force leads to a deflection of the missile from the assigned direction. For calculating the flight trajectory it is necessary to know the value of the Magnus force and the point of its application.

Experiments [1-4] have shown that the value and direction of the effect of the Magnus force depend on both the geometry of the missile (shape of the body and its elongation, the presence of a fin and the method of its attachment) and on the mode of flow (angle of attack, rate of rotation, M_∞ and Re numbers). Limited experimental data obtained mainly for short bodies do not permit reliable determination of the value of Magnus forces and moments which act on a body with a certain design. Analytically this problem, even at small angles of attack (non-breakaway flow), has been studied in a very approximate form. An experiment becomes quite important under these conditions.

For experimental study of the Magnus effect on bodies of revolution of great elongation a special set-up was developed which was fastened on to an acinaciform suspension of a wind tunnel. The set-up provided the necessary position of the model in the working part of the tunnel, created rotation of the model with the necessary angular velocity and with fixation of the number of revolutions and also made it possible to measure the lateral force Z and the yawing moment M_y . The lateral force and its moment were measured using tensometric scales designed for a load up to 0.5 kg with respect to force and up to 0.35 kg with respect to moment. For preventing the effect of a shock wave during starting and stopping of the wind tunnel the tensometric scales were mechanically disconnected, i.e., they were stopped. The basic assemblies for studying the Magnus effect: model 1 which is fastened on holder 2, supported on bearings 3 and 4, reverse direct current electric motor 5 with a photoelectric tachometer for measuring the number of revolutions of the model (n $\leq$

8000 r/min), two-component tensometric scales 6, a locking device with electromagnetic drive 7 and a mechanical drive 8. The entire construction was covered with a coul 9 (Fig. 1).

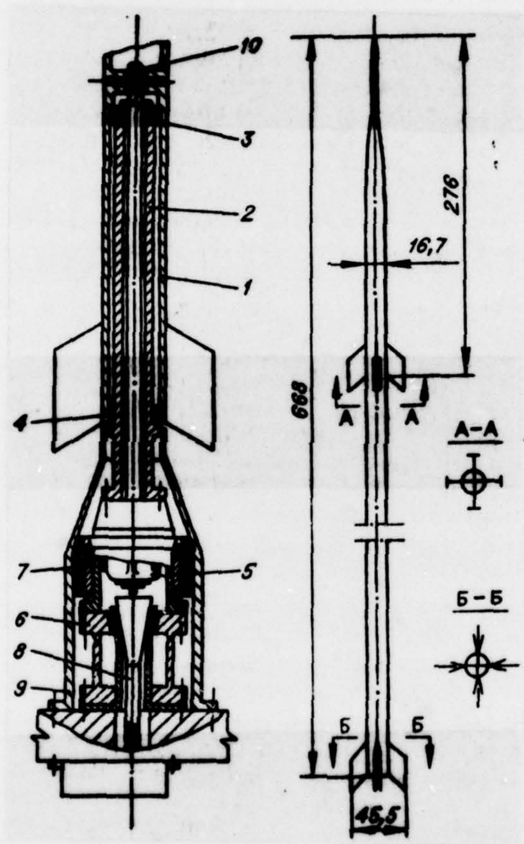


Fig. 1. Structural diagram of a set-up for studying the Magnus effect.

A hollow cylinder with an ogival nose part and spire serves as the model. Two cross-shaped fins are located on the body. The overall elongation of the model $\lambda = l/d = 40$ (l and d are the length and diameter of the model). Rotation of the model by the electric motor is accomplished using a central rod 10 which freely passes through the inside of the holder.

In the course of preliminary experiments without flow a check was made of the stability of revolutions of the model with a fixed power of the electric motor, of the stability of the position of the axis of the model with various numbers of revolutions and the degree of its deformation under the effect of a concentrated load, of the efficiency of the locking device and also of the calibration of the tensometric scales.

Experiments were conducted in a supersonic wind tunnel ITPM T-313 with $M = 4$, $Re_l = 37 \cdot 10^6$ and angles of attack α from 0 to 15°. The modeling parameter $\varepsilon = \omega d/2U_\infty$ changed in the range of $(1.4-9.4) \cdot 10^{-3}$, which corresponded to a number of revolutions of the model of n = 1000-7000 r/min or an angular velocity of ω = 105-735 1/s.

The measuring process was reduced to the following. The signal from the tensometric scales which characterizes the total lateral force or the resulting moment enters the electronic device DACQ-2BB, which is a multiple-point system of automatic collection and accumulation of information (manufacturer - Takeda-Riken, Japan). Here the signal is amplified and averaged in time due to which it is possible to exclude its pulsation component. Pulsations arise mainly from the wobble of the rotating model and from fluctuations of the flow. The averaged signal in digital form is output onto the tape of a printer for subsequent processing.

During measurements of Magnus forces and moments an important role is played by the correct selection of the reading point (zero or initial reading N_0). For N_0 a value N should be chosen (reading of the DACQ) not with a zero number of revolutions (n=0) but as a limiting value with $n \to 0$. The tests showed a very good reproducibility of values $N|_{n\to 0}$ (dynamic zero) and a noticeable spread $N|_{n=0}$ (static zero). The latter is connected with the fact that the model rotating on a relatively thin holder is more inert to the effect of fluctuations of flow and therefore its position is more stable in comparison with a non-rotating model, particularly with large elongations.

Thus for the initial reading N_0 the dynamic zero $N|_{n\to 0}$, was chosen. It was determined from the relationship

(1) $$N_0 = N|_{n\to 0} = \frac{N|_{n_+} + N|_{n_-}}{2}.$$

Values $n_+=|n_-|$ were selected equal to 1000 r/min. The value of the Magnus force or moment was determined from the difference

(2) $$\Delta N_n = N_n - N_0,$$

where N_n is the reading of the instrument with a given number of revolutions of the model.

During the experiment various types of errors are added to the measured value. They may be divided into three types: 1) errors which are constant with a given angle of attack (wash of the flow in the tunnel, inaccuracy in placement of the tensometric scales, etc.); 2) errors which change their value in time (the effect of temperature on the tensometric scales); 3) errors, the value and sign of which depend on the direction and velocity of rotation of the model.

Errors of the first type are mutually exclusive during subtraction of the results of measurements according to (2). Errors of the second type are taken into account using control measurements of Magnus forces with one and the same number of revolutions n = 1000 r/min. Such measurements took place at approximately equal intervals of time $\Delta\tau$ and were alternated with measurements of other (assigned according to a program) numbers of revolutions of the model. The obtained dependence $\Delta N(\tau)$ makes it possible to find the necessary correction for any reading.

The third type of error is connected with the fact that under the effect of the Magnus force Z a certain angle of slip $\Delta\beta$ appears. In this case a supplementary force ΔZ arises which acts parallel to force Z. In the presence of lift force $Y = Y(\alpha)$ the axis of the model also deviates from the assigned direction by angle $\Delta(\alpha)$. The indicated deviations $\Delta\beta$ and $\Delta\alpha$ take place mainly due to deformation of the holder in the section immediately behind the base section of the model. The axis of the rotating model in this case remains almost rectilinear. For calculating values ΔZ and $\Delta\alpha$ it is necessary to have the dependence of the lift coefficient on the angle of attack and the dependence of the degree of deformation of the axis of the model on the value of the moment of the applied force. Estimates show that force ΔZ comprises not more than 5 $^0/_0$ of the measured value Z. In the test results cited below this correction was not taken into account.

The accuracy of measurements depends not only on the factors noted above but on the sensitivity of the tensometric scales and on the resolution of the instrument DACQ and the stability of its readings with a constant value of the measured value. The error arising in this case (track of spread) is ± (1-2) units with a measured value from zero to 40 units.

The method of making and processing measurements which was used in the tests made it possible to separate from the total of forces acting on the model only the dynamic (connected with rotation) component. In the absence of rotation this component is equal to zero.

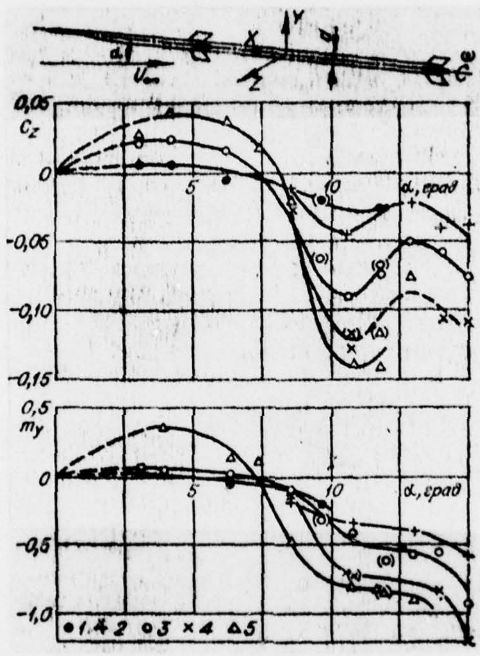
With respect to the measured value of the Magnus force Z and the moment of this force relative to the bottom section of the model, the coefficients of forces and moments were determined

(3) $$C_z = \frac{Z}{qS} \text{ and } m_y = \frac{M_y}{qSd}.$$

Here q is the dynamic pressure; S is the area of the middle.

Dependences of the coefficients of Magnus forces and moments on the angle of attack with various velocities of rotation of the model, i.e., with various values of the parameter ε, are shown in Fig. 2.

Fig. 2. Coefficients of Magnus forces and moments with M = 4 and Re_l = 37•10⁶. ε = 0.0014 (1); 0.0027 (2); 0.0054 (3); 0.0081 (4); 0.0094 (5). ( ) - values (with inverse sign) obtained during rotation of the model in the opposite direction. KEY: 1) degree.



It is evident that coefficients C_z and m_y are in a complex dependence on the angle of attack changing both in value and in sign. These changes are caused by the different nature of Magnus forces. In the first place the classic Magnus force Z_1 acts on the studied body. It arises dring rotation of an unfinned cylindrical body in a flow at an angle of attack. Second there is the force Z_2 caused by the fact that the plates of the fin which are located on the lee and windward sides of the model are submerged into a boundary layer of varying thickness. As a result an unbalanced lateral force appears which is opposite to the classical Magnus force with respect to the direction of its effect and the point of its application is located on the fin [3]. Third, on the plates of the tail fin a lateral force Z_3 arises which is caused by the effect of vortices coming off of the front fin and from the surface of the body. The direction of the effect of this force is is also opposite to the direction of the classic Magnus force.*

[FOOTNOTE: *Although lateral forces Z_2 and Z_3 are different (in comparison with the Magnus force Z_1), by analogy they are sometimes also called Magnus forces. END FOOTNOTE]

At small angles of attack ($\alpha \leqslant 5°$) the model is acted on chiefly by the force Z_1 and the effect of the fin is small. In this range of change α force Z increases which qualitativlely agrees with the data of work [5].

At angles of attack $\alpha > 5°$ the Magnus force and moment decrease to zero and then reach large negative values.*

[FOOTNOTE: *The direction of the Magnus force coinciding with the direction of the effect of the classic Magnus force is considered to be positive. END FOOTNOTE]

This is apparently explained by the fact that in a certain range of angles of attack the forces Z_2 and Z_3 are dominant. With $\alpha > 10°$ the absolute values of Magnus forces decrease somewhat since part of the vortices coming off of the front fin is carried away by the flow and does not interact with the tail fin.

Concerning the effect of the rotation of the model (i.e., parameter $\bar{\omega}$) on the value of the Magnus force and moment, for the studied model in the range of angles of attack $0 < \alpha \leqslant 15°$ these dependences are close to linear.

Fig. 3 shows coordinates $X_z = M_y/Z$ of points of the application of the resultant Magnus force depending on the angle of attack α with different values of parameter ε.

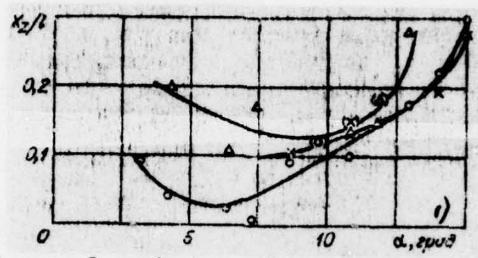


Fig. 3. Coordinates of points of application of the resultant Magnus force with M = 4. Designations are the same as in Fig. 2.
Key: 1) degree.

The dimensionless coordinate $\bar{X}_z = X_z/l$ is read off from the base section of the model. The relatively large spread of the obtained points in the range α = 6-9° is explained by the fact that the values Z and M_y in the indicated range of angles of attack are close to zero. The character of the behavior of $\bar{X}_z(\alpha)$ is determined by the relationship of forces Z_1, Z_2, Z_3, and the corresponding moments for each angle of attack. With $\alpha \to 0$ one notes a tendency twoard displacement of the point of application of the resultant force Z to value $\bar{X}_z \approx 0{,}3$. The position of coordinate $\bar{X}_z$ for a shell without a fin with $\alpha \to 0$ corresponds to this value which is in agreement with the data of work [5].

CONCLUSIONS

The suggested construction of the set-up and the developed method of measurement make it possible with satisfactory accuracy to measure the resultant Magnus force and moment on a rotating finned body of revolution with an elongation up to λ = 40. The results of experimental research showed that with small angles of attack the Magnus force is positive. However, with a subsequent increase of α it sharply changes the direction of effect to the opposite direction and increses significantly in size. In this case the point of its application is displaced in the direction of the nose part of the model. For the examined make-up the change in the direction of the effect of the lateral force takes place at angles of attack of α = 6-7°.

The absolute values of the Magnus forces and moments increase with an increase in parameter ℓ; these dependences are close to linear.

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Institute of Theoretical and Applied Mechanics Siberian Department AS USSR, Novosibirsk

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