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THE DRAG OF MAGNETICALLY SUSPENDED WIND-TUNNEL MODELS WITH NOSE-CONES OF VARIOUS SHAPES

George Dubois

Translation of "Trainees de maquettes de soufflerie comportant des ogives de formes variees en suspension magnetique," La Recherche Aeronautique, number 87 - 64, March-April, 1962, pp. 47-54.

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16. Abstract

This article concerns the experimental determination of optimum nose-cones (minimum drag) of a body of revolution at supersonic and hypersonic speeds by means of ONERA magnetic suspension.

The study concerns two groups of models, specifically: a group whose nose-cone has a profile in the shape of X^n; the AGARD B group whose nose-cone is plotted in accordance with a given law.

The results obtained for the first group are comparable to those calculated with the approximations of Cole and Newton, and the experiments carried out by Kubota.

This study carried out as a result of suggestions by Mr. Henri Le Boiteux, Scientific Civics Director at ONERA was conducted in a small hypersonic wind tunnel of ONERA, installed in the Laboratory of Physical Mechanics of the Advanced School of Industrial Physics and Chemistry (ESPCI) in collaboration with M. Bessac, engineer of the ESPCI, then a fourth year student.

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THE DRAG OF MAGNETICALLY SUSPENDED WIND-TUNNEL MODELS WITH NOSE-CONES OF VARIOUS SHAPES

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Quantities and Notations /47*

Angle

θ : angle of the tangent to the profile at the point (x,y).

Lengths

R and D, radius and diameter of the model (mainframe).

L = length of the model;

l = height of the nosecone;

h = height of the blunted AGARD B nose-cone;

ρ = radius of the tip of the blunted AGARD B nose-cone.

Surfaces

S = reference area (mainframe).

Pressures

p_i = generating pressure;

p'_i = stopping pressure;

p_0 = infinite pressure upstream (experimental section);

p = pressure at the point (x,y) of the profile (nose-cone);

q_0 = kinetic pressure = $\frac{\gamma p_0 M_0^2}{2}$

*Numbers in the margin indicate pagination in the foreign text.

Forces

R_{xp} = pressure drag = $C_{jp}q_0s$:
R_x = total drag = C_xq_0s.

Nondimensional Coefficient

λ = l/D = elongation of the nose-cone;
ρ /R = relative radius of the tip of the nose-cone;
n = exponent of the equation of the profile of the nose-cone ($y \sim x^n$);
M_0 = mach number of the experimental section;
R_L = Reynolds number referred to the length of the model;
R_l = Reynolds number referred to the height of the nose-cone;
K_p = pressure coefficient: $= \frac{p - p_0}{q_0}$
C_{xp} = pressure drag coefficient;
C_x = total drag coefficient;
C_{xf} = friction drag coefficient.

I. Introduction

I,1. We know that the Newtonian approximation makes it possible to determine the nose-cone of minimum resistance; it is on the basis of this scheme that we tested two groups of models for variable Mach numbers so as to determine this nose-cone.

I,2. Newtonian Flows

The Newton scheme leading to the following expression of the pressure coefficient (fig. 1):

$$K_p = \frac{p - p_0}{q_0} = 2 \sin^2 \theta = \frac{2 y'^2}{1 + y'^2} \qquad (1)$$

if $y = f(x)$ is the equation of the profile considered, is reduced for slender bodies to $K_p = 2tg^2 = 2y'^2$ (2)
(sine $\theta \sim \theta \sim tg\theta = y'$).

Taking into account the fact that the presence of the profile perturbs the flow in contact with the body and obtaining the balance of the quantities of motion, Cole /1//2//3/ finds that the correction term yy'' must be added to expression (2): /48

$$K_p = 2y'^2 + yy'' \quad (3)$$

On the basis of this theory Cole obtains a particularly interesting group of nose-cones of revolution of the shape $y \sim x^n$. Introducing the value of K_p (3) in the expression of the pressure drag coefficient,

$$C_{xp} = \frac{R_{xp}}{q_0 S} = \frac{8}{D^2}\int_0^l K_p y y' \cdot dx \quad (4)$$

(S = mainframe = $\frac{\pi D^2}{4}$), a simple calculation gives for a nose-cone which meridian is:

$$\frac{y}{D/2} = \left(\frac{x}{l}\right)^n \quad (5)$$

$$C_{xp} = \frac{n^2}{4\lambda^2}\frac{3n-1}{2n-1} \quad (6)$$

$\lambda = \frac{l}{D}$ being the elongation of the nose-cone;

n = 1: cone;
n = ½: paraboloid of revolution.

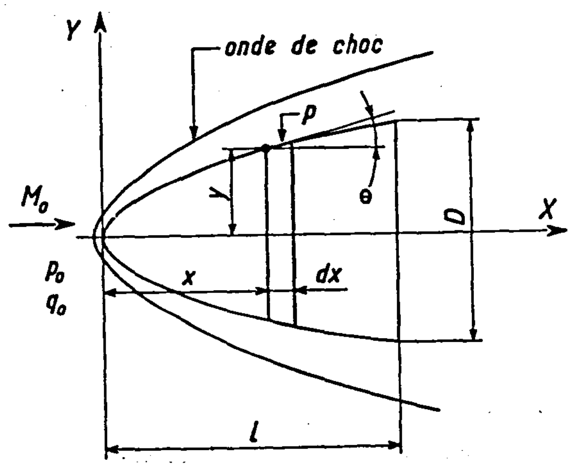

Fig. 1: Elongation of the nose-cone: = 1/D.
Key: (1) shockwave

The drag coefficient C_{xp} is minimum for $n = \frac{2}{3}$. The only acceptable value, because the necessary condition is:

$$\frac{1}{2} \leqslant n \leqslant 1.$$

The curves C_{xp}/C_{xp} cone as a function of n is specified on fig. 11 (Cole)(see appendix 1).

If in the expression (4) K_p is replaced by value (1) (Newton approximation), we obtain:

$$C_{xp} = \frac{16}{D^2} \int_0^l \frac{yy'^3}{1 + y'^2} dx. \qquad (7)$$

The minimum C_{xp} corresponds to a certain function determined on the basis of the previous expression (7). A.J. Eggers, J.R. Meyer, M. Resnikoff and David H. Dennis /4/ found that the theoretical profile is actually very close to the simple profile y~x 3/4. The calculations of C_{xp} have been carried out for n = 1, 3/4, 2/3 and 1/2 (see appendix 2) and the curve $C_{xp}/C_{xp\ cone}$ was plotted as a function of n, fig. 11 (Newton).

II. Experimental Arrangements

II.1 Means of Investigation

The test on the model defined in number 22, were carried out in a hypersonic wind tunnel with gusts of the ONERA.

The drag was measured with the ONERA magnetic suspension method described in articles /5/ and /6/.

In this wind tunnel in which the Mach number varies for these tests from 3.75 to 6.3, the adjustable generating pressure from 0.5 50 8 atm makes it possible to obtain a Reynolds number per cm between 10^4 and 7 by 10^4.

Since the models have small dimensions (D = 6 mm, L = 60 mm) the Reynolds number referred to the length of the body is low; at maximum $R_1 \simeq 4$ by 10^5. This corresponds if the model is on the scale 1/100 of an aircraft flying at M = 5, to an altitude of the order of 50 km.

It may be noted that the static pressure p_0 in the experimental section is, according to the value of the previous quantities, between 100 and 1500 pascals.

All the measurements are recorded without any difficulty as a function of time (time of the gust $\simeq$40 seconds).

II.2 Definition of the Models

Two groups of models were chosen:

a) group $y \sim x^n$ (figs. 2 and 3).

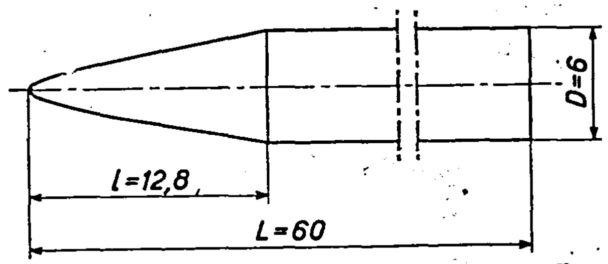

Fig. 2: Model: cylinder plus nose-cone, $y \sim x^n$: (case n = 2/3). Elongation of the nose-cone: λ = 2.13.

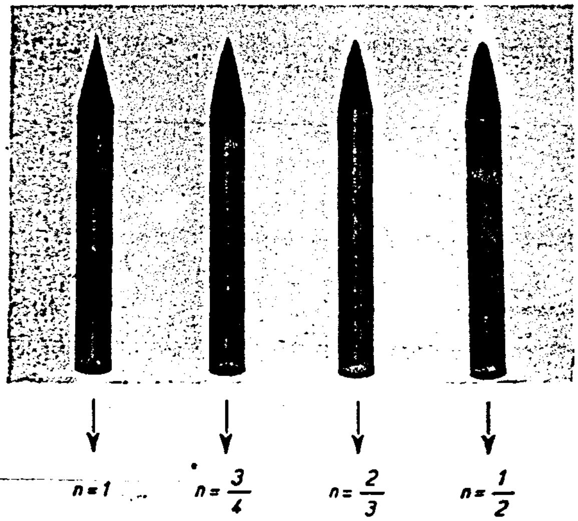

Fig. 3: Models in x^n (nose-cone).

These models consist of a straight cylinder and a nose-cone whose profile is given by: /49

$$y = \frac{D}{2}\left(\frac{x}{l}\right)^n$$

n = 1, cone;

n = 3/4;

n = 2/3;

n = 1/2 (paraboloid of revolution).

To have an element of comparison, we took again the models tested by Kubota /3/ who determined their pressure drag coefficient C_{xp}.

These models have an elongation nose-cone:

$$\lambda = 1/D = 2.13.$$

Note: According to Kubota's notations, is replaced by:

$$\delta = \frac{D}{2l} = \frac{1}{2\lambda} = 0.235.$$

b) AGARD B group, elongated to 10 D (the AGARD B model has an elongation of 8.5 D) (fig. 4).

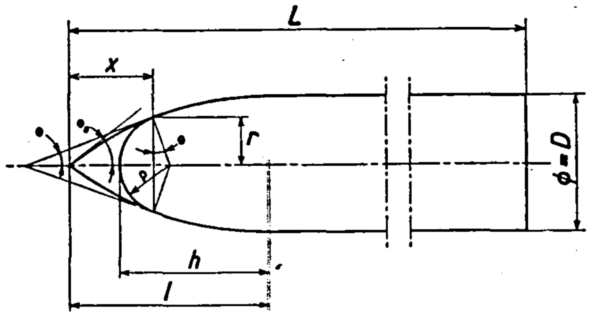

Fig. 4: Elongated AGARD B model (10 D). Nose-cone: length = 3 D (model number 1). θ_0 = 18°26', D = 6 mm; L = 60 mm, l = 18 mm

Nose-cone:

Elongation: $\lambda = \frac{l}{D} = 3$ (model number 1).

Equation of the profile (type A, by Mr. Maurice Roy):

$$r = \frac{x}{3}\left[1 - \frac{1}{9}\left(\frac{x}{D}\right)^2 + \frac{1}{54}\left(\frac{x}{D}\right)^3\right].$$

Blunted models, number 2, 3, and 4 according to the scheme specified on fig. 4.

h = height of the blunted nose-cone (variable);

$h = l - x + \rho - r \operatorname{tg} \theta$

with $\rho = \frac{r}{\operatorname{tg}\theta}$

The elongation λ of the nose-cone is specified in fig. 5 as a function of the relative radius of the tip ρ/R.

Note: The control of each nose-cone was carried out with the profile projector. The dimensions are respected to within plus or minus 0.01 mm.

II.3 Calibration of the Drag

A very thin wire, fixed to the base of the model is connected with an auxiliary balance (fig. 6). The effort applied is automatically balanced by the current passing through the so-called drag coil. This current is measured (deviation of the spot) and a calibration curve is plotted for each model.

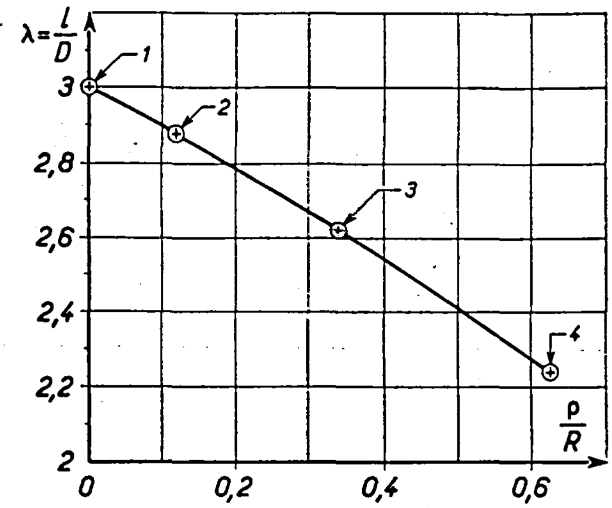

Fig. 5: Elongation of the nose-cone as a function of the relative radius of the tip $\frac{\rho}{R}$.

1. Model number 1 (AGARD B) ($x = 0$, $\frac{\rho}{R} = 0$).
2. Model number 2 ($x = 1$, $\frac{\rho}{R} = 0.117$).
3. Model number 3 ($x = 3$, $\frac{\rho}{R} = 0.34$).
4. Model number 4 ($x = 6$, $\frac{\rho}{R} = 0.624$).

Remark: The curves specified on fig. 6 show that for a same force the current varies according to the shape of the profile of the nose-cone. Actually since the models in x^n have the same length, the more rounded the nose-cone, therefore the more magnetizable matter it contains, consequently the lower the current has to be for a given force.

Thus for a force of 12 g we have: for the cone ($n = 1$) a deviation of the spot of 159 mm, and for the paraboloid of revolution ($n = 1/2$) for 148.5 mm.

II.4 Specification of the Measurements

- generating pressure p_i: $\pm$ 0.5 %;
  stopping pressure p_i: $\pm$ 0.5 %;

static pressure (experimental section): ± 1 %; /51

Mach number M: ± 1 %.

Drag R_x: ± 0.5 % for R_x = 7 grams;

± 1 % for R_x = 3 grams.

Drag coefficient: $C_x = \frac{R_x}{qS}$

Negligible error on S (± 0.1 %):

$\left|\frac{\Delta C_x}{C_x}\right| \leq 1\%$; for low drag (± 2 percent). /50

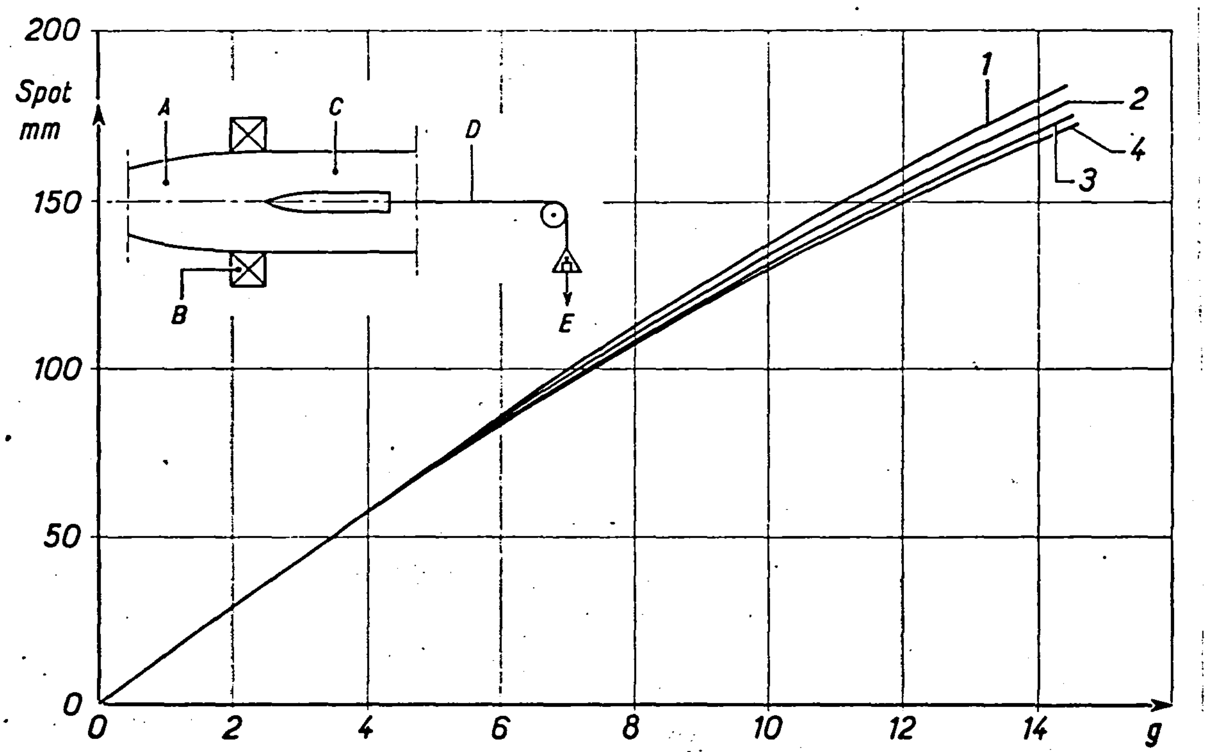

Fig. 6: Calibration of the balance 1: n = 1 2: n = $\frac{3}{4}$ 3: n = $\frac{2}{3}$ 4: n = $\frac{1}{2}$ A. nose-cone; B. drag coil; C. experimental section; D: wire (nylon 20 μ) E. grams.

III. Experimental Results

III,1. For each model and for a given Mach number, C_x total was determined as a function of the Reynolds number R_L whose variation was obtained from that of the generating pressure p_i.

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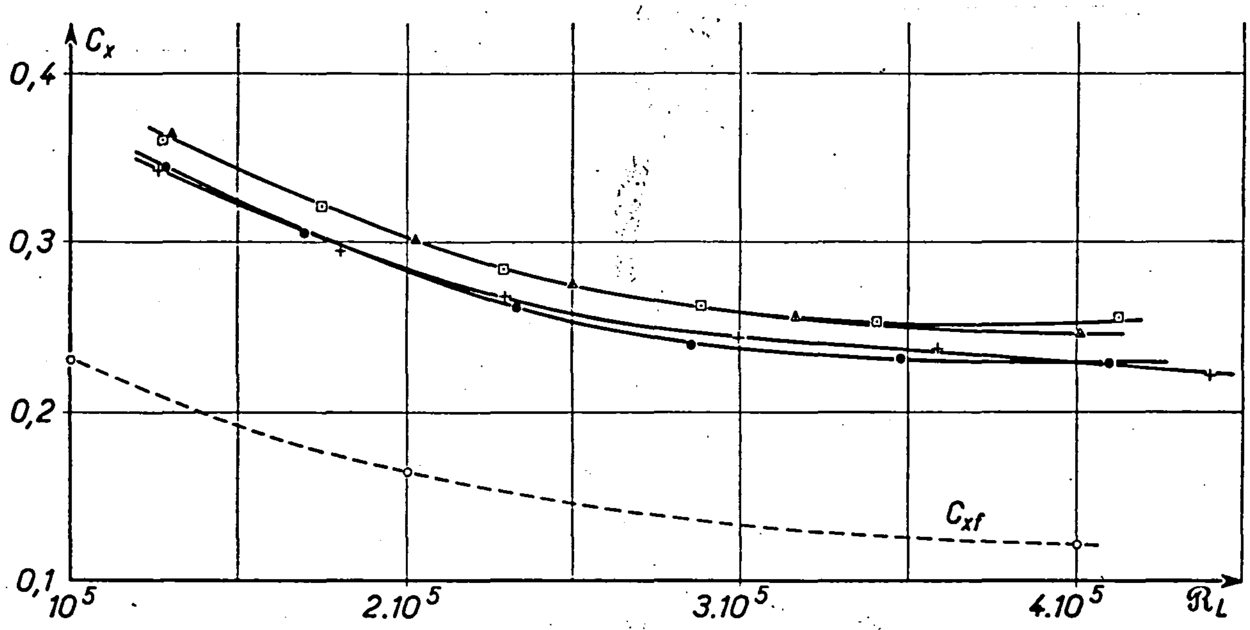

Fig. 7. — M ≃ 3,75 p_i = 0,3 à 2 atm. Δ n = 1 □ n = 1/2 ● n = 2/3 + n = 3/4.

III.2 Group of Models with Nose-Cones in the Shape of x^n /51

The results are specified in figs. 7, 8, 9 and 10.

As may be observed, for low R_L the C_x is 1.5 to 2 times greater than when R_L has the largest value; the limiting laminar layer on the profile is thickened as R_L decreases and in corrolation the total C_x increases, very consistently with theoretical predictions (fig. 7).

To compare our results with those calculated from the approximations of Cole and Newton and the experiments of Kubota /3/, we plotted on fig. 11 the curve $C_{xp}/C_{xp\ cone}$ and $C_x/C_{x\ cone}$ as a function of n.

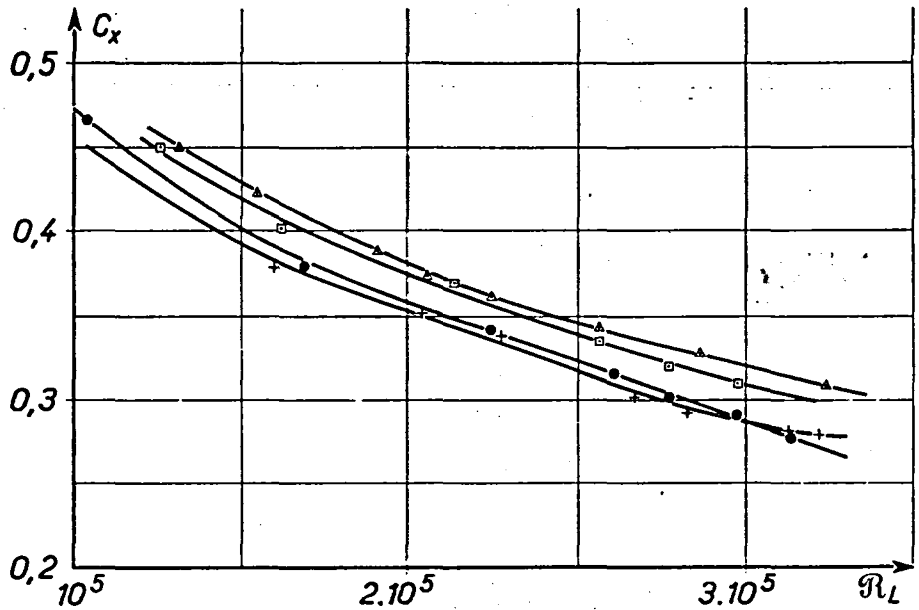

Fig. 8. — M ≃ 4,8 Δ n = 1 □ n = 1/2 ● n = 2/3 + n = 3/4 p_i = 0,9 à 4,1 atm.

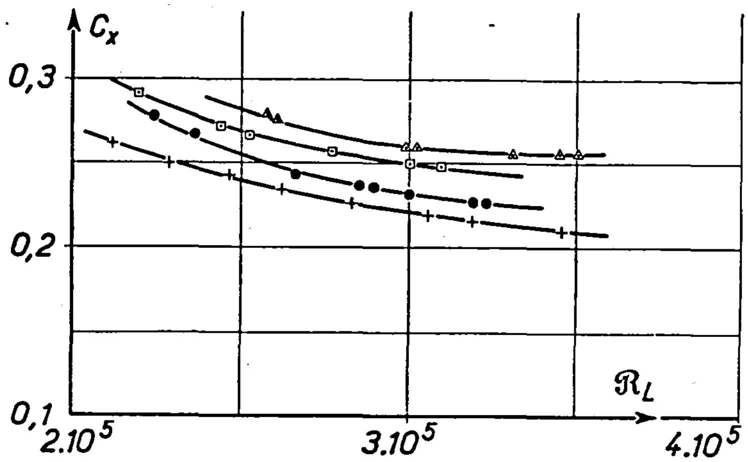

Fig. 9. — M = 5,3 Δ n = 1 □ n = 1/2 ● n = 2/3 + n = 3/4.

These curves in Table number 1 indicate that the minimum C_x is obtained for n 2/3, M varying from 3.75 to 4.8 and n 3/4 for M 4.8. The tendency is rather towards 3/4. /52

Table 1

(1) Valeurs du rapport $C_{xp}/C_{xp\ cône}$ $\lambda = l/D = 2{,}13$				(2) Valeurs du rapport $C_x/C_{x\ cône}$ $\lambda = l/D = 2{,}13$ Expériences ONERA Soufflerie S2.PC			
n	Approx. COLE	Approx. NEWTON	Expér. KUBOTA M = 7,7	M = 3,75 $\mathcal{R}_L = 3.10^5$	M = 4,8 $\mathcal{R}_L = 3.10^5$	M = 5,3 $\mathcal{R}_L = 3.10^5$	M = 6,3 $\mathcal{R}_L = 2.10^5$
3/4	0,702	0,84	0,905	0,94	0,90	0,85	0,91
2/3	0,666	0,852	0,882	0,92	0,90	0,89	0,95
1/2	∞	1,132	1,155	1	0,96	0,97	0,98

Key: (1) values of the ratio $C_{xp}/C_{xp\ cone}$; (2) values of the ratio $C_x/C_{x\ cone}$, = 1/D = 2.13 ONERA Experiments S2.PC wind-tunnel.

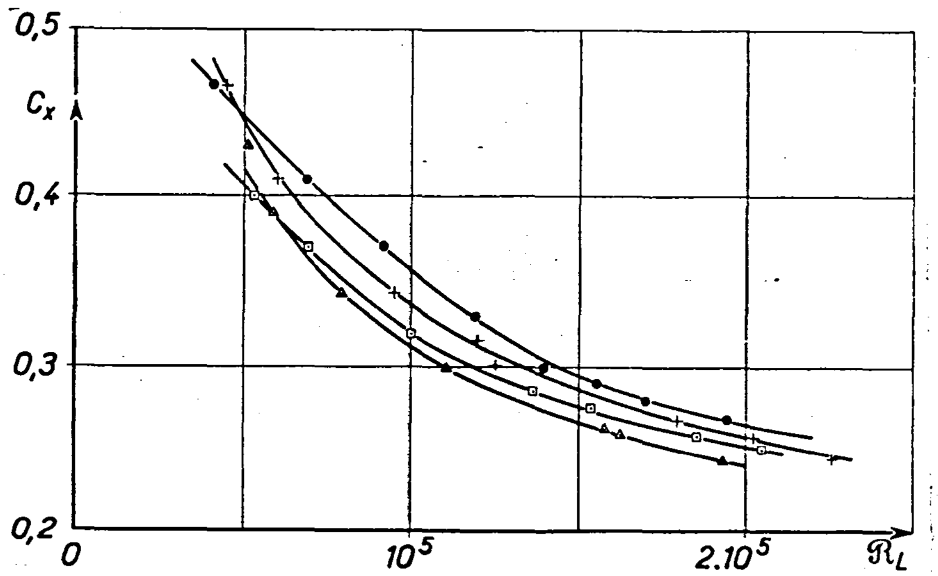

Fig. 10: $M \simeq 6{,}3\ x^n$ { ● $n = 1$; + $n = 1/2$; □ $n = 2/3$; Δ $n = 3/4$ }

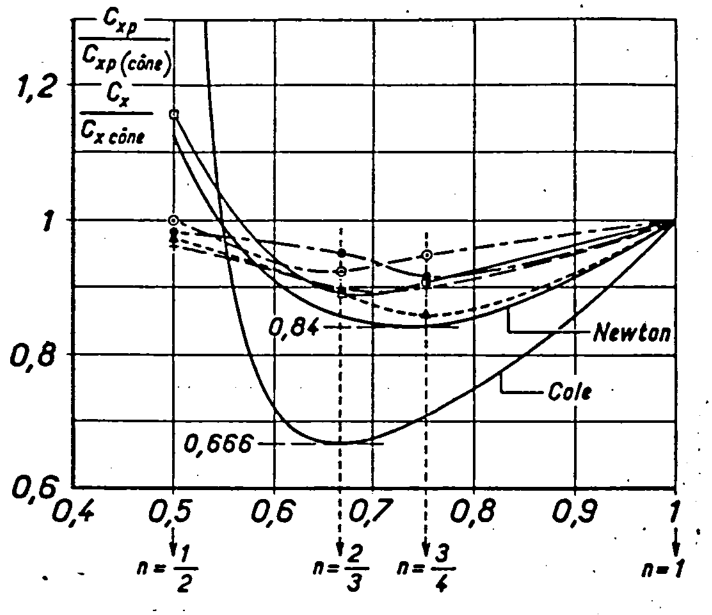

Fig. 11: λ= 2.13 Experiments of Kubota. □ $M = 7.7$ $R_l/cm = 6{,}8.\,10^4$

Elongation of the nose-cone λ= 2.13. Experiments in the S 2 PC wind tunnels (ONERA)

O $M \simeq 3{,}75$; + $M \simeq 4{,}8$; Δ $M \simeq 5{,}3$ — $R_L = 3.10^5$, $R_l = 6{,}4.10^4$.
● $M \simeq 6{,}3$ — $R_L = 2.10^5$, $R_l = 4{,}3.10^4$.

III.3 Group of Blunted AGARD B Bottles

The curves of fig. 12 show that the minimum C_x is obtained with model number 2 whose nose-cone is very slightly blunted ($\rho/R = 0.117$).

The effect on C_x of the roundness of the tip indicated in fig. 13 for $R_L = 300{,}000$.

IV. Conclusions /53

The magnetic suspension allows precise measurement of the drag of bodies of revolution.

The few results obtained on models in the shape of x^n and blunted AGARD B indicate that at high speeds (M = 3.75 to 6.3) and for Reynolds number between 10^5 and 4 by 10^5, slightly rounded nosecones are less resistant than pointed nose-cones. Thus the profiles $y \sim x^{2/3}$ in supersonic conditions and $y \sim x^{3/4}$ in hypersonic conditions seem to correspond to the optimum in this respect.

The same holds true for the slightly blunted AGARD B profile (radius of the tip in the order of tenth of the radius of the model).

The advances achieved in the technique of magnetic suspension will allow such measurements of C_x at higher Mach numbers, in a larger range of Reynolds numbers with simultaneous remote measurement of the base pressure, an indispensable element for a complete discussion of the tests.

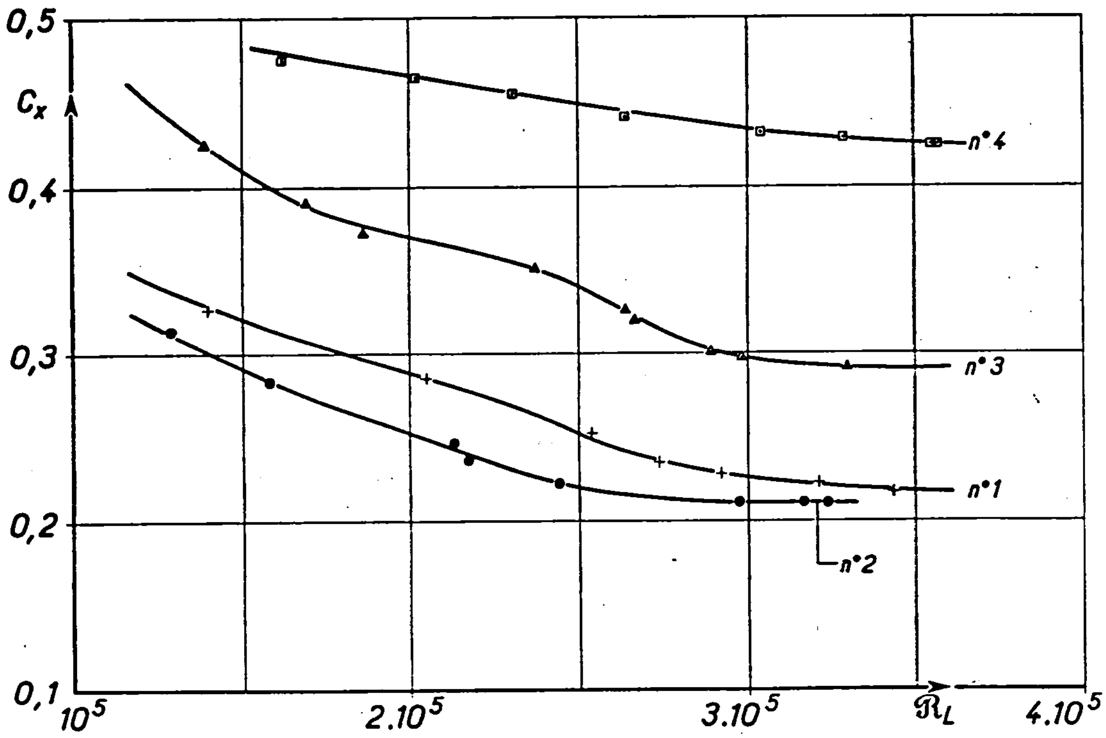

Fig. 12 — AGARD B : M = 5,3
n° 1 + $\rho/R = 0$, $x = 0$.
n° 2 ● $\rho/R = 0,117$, $x = 1$.
n° 3 Δ $\rho/R = 0,34$, $x = 3$.
n° 4 □ $\rho/R = 0,624$, $x = 6$.

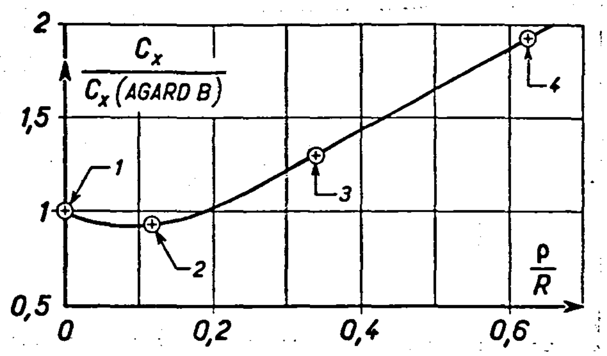

Fig. 13: Effect on the roundness of the tip on C_x.
R_L = 300,000 $\frac{\rho}{R}$ relative radius of the tip.

Appendix I

Approximation of Cole

Taking an expression (6) n = 1, 3/4, 2/3 and 1/2, we find (fig. 11):

$n = 1$ (cône) $C_{xp} = \frac{1}{2\lambda^2}$

$n = 3/4$ $\quad C_{xp} = \frac{45}{128\lambda^2}, \quad \frac{C_{xp}}{C_{xp\ cône}} = 0{,}703$ (paraboloid of revolution).

$n = 2/3$ $\quad C_{xp} = \frac{1}{3\lambda^2}, \quad \frac{C_{xp}}{C_{xp\ cône}} = \frac{2}{3} = 0{,}666$

$n = 1/2$ $\quad C_{xp} = \infty, \quad \frac{C_{xp}}{C_{xp\ cône}} = \infty$

Appendix II

Approximation of Newton

Starting from the expressions (5) and (7) and introducing the elongation of the nose-cone

$$\lambda = \frac{l}{D}$$

the following expressions are found for the pressure drag coefficient C_{xp}:

$n = 1$ (cône) $\quad C_{xp} = \frac{2}{4\lambda^2 + 1}$

$n = 3/4 \quad C_{xp} = \frac{3}{\Gamma^2}\left[1 - \frac{2}{\Gamma^2} + \frac{2}{\Gamma^4} \text{Log}\,(\Gamma^2 + 1)\right]$

taking

$$\Gamma = \frac{8\lambda}{3}$$

$n = 2/3 \quad C_{xp} = \frac{4}{9\lambda^2}\left[1 - \frac{1}{9\lambda^2} \text{Log}\,(9\lambda^2 + 1)\right]$

$n = 1/2$ (paraboloid of revolution)

$$C_{xp} = \frac{1}{8\lambda^2} \text{Log}\,(16\lambda^2 + 1).$$

For $\lambda = 2.13$ (tested models) we find the following values for the ration $C_{xp}/C_{xp\ cone}$: 0.84 for n = 3/4, 0.852 for n = 2/3 and 1.132 for n = 1/2 (curve fig. 11).

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