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SOME DEVELOPMENTS IN WIND TUNNEL DESIGN

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SOME DEVELOPMENTS IN WIND TUNNEL DESIGN

1. INTRODUCTION:

The Wind Tunnel is a well established aerodynamic tool for solution of many complex problems which arise in the design of aircraft. The increasing speeds and altitudes of flight have had their effect on the development and design of aerodynamic test facilities. Thus transonic flight called forth the ventilated wall Wind Tunnel while now the possibilities of hypersonic and sub-orbital flight have emphasised the need for hypersonic high enthalpy shock tunnels. Another area which is developing quite rapidly is the VTOL/STOL field where aircraft landing and take-off speeds are sought to be made independent of runway limitations. In terms of Aerodynamic Test Facilities this latter development calls for low speed Wind Tunnels with exceptionally smooth air flow at speeds of the order of 10 - 15 ft/sec. and test section sizes in the neighbourhood of 15 ft x 15 ft. This talk is concerned with two specific problems:

(a) The use of ventilated walls for reduction of lift interference effects in low speed Wind Tunnels,

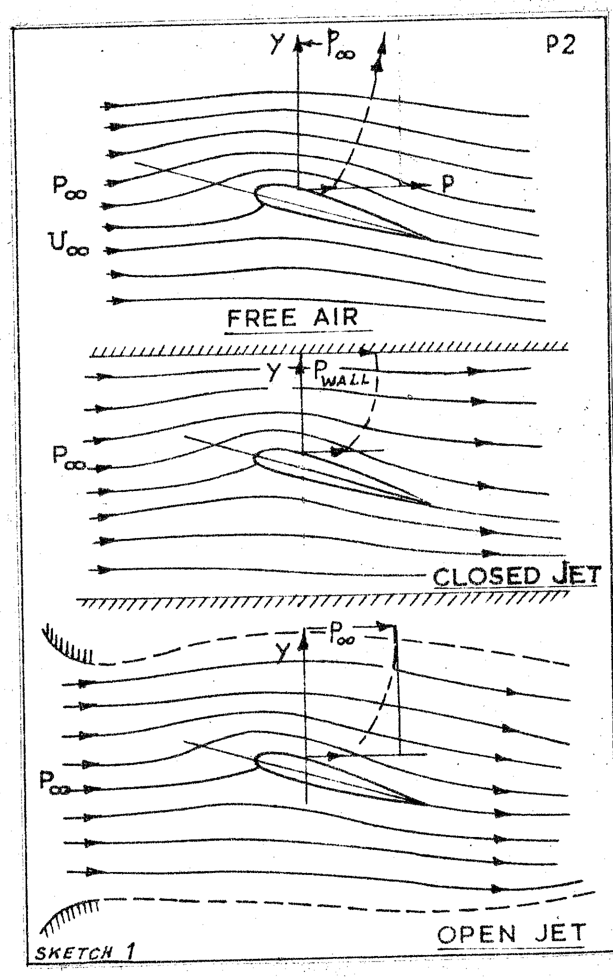
and (b) Some problems which arise in the design of a VTOL/STOL Wind Tunnel.

Both of these have arisen out of recent work in the Department of Aeronautics, Indian Institute of Science, Bangalore.

2. USE OF VENTILATED WALLS FOR REDUCING INTERFERENCE IN A LOW SPEED WIND TUNNEL:

Ventilated walls were originally developed in response to the Mach No. limitation which a conventional high speed Wind Tunnel suffers, i.e. choking and large interference effects as the free stream Mach No.

approaches 1.0. Actually the basic principles of the semi-open type of test section have been known for a long time but it is only with the development of transonic Wind Tunnels that a sufficiently detailed understanding of the flow phenomenon been achieved. It is well known that at low speeds the interference effects in a closed and open type of test section are of opposite sign and roughly equal in magnitude.



The streamline patterns around a wing in free flight differs from one produced by the same wing in a confined space because the streamlines in a wind tunnel are constrained by the boundary of the Test Section. The velocity perturbation produced by the wing slowly dies off in the lateral direction.

<u>Closed Jet:</u>

If the Wind Tunnel is a closed one the flow must be tangential to the wall. If U_∞ = free stream and U, v, the velocity components at any point and $U = U_\infty + u$ then we can define a velocity potential such that

$$\Phi = U_\infty x + \phi$$

where ϕ is the perturbation potential whose derivatives define u, v and w. The boundary condition for the closed jet then becomes

$$v = \frac{\partial \phi}{\partial n} = 0 \text{ on walls.}$$

Open Jet:

The condition to be satisfied at the jet boundary now becomes p = constant across the jet since the free boundary cannot support a pressure differential across it.

Thus $P - P_\infty = \Delta P = 0$

Now a well known result of small perturbation (linearized) flow theory is

$$C_p = \frac{\Delta P}{\frac{1}{2}\rho U_\infty^2} \doteq -2\frac{u}{U_\infty}$$

thus for the free jet $\frac{u}{U} = 0$ or $\frac{\partial \phi}{\partial x} = 0$ at the jet boundary; this equation may be applied approximately at the undisturbed jet boundary, i.e. at y = constant since the distortion is small. Then integrating along the jet direction we get

$$\phi = \text{Constant on free jet boundary}$$

and since the disturbances must die out far upstream we get $\phi = 0$ as the boundary condition. Thus for free jet we have

$$\frac{\partial \phi}{\partial x} = 0$$

on jet boundary

or $\phi = 0$

It is instructive to note that for a free jet the pressure build up in the lateral direction (see sketch) must be faster than for the free air case - this is because the free stream pressure must be attained sooner (at jet boundary) in the former case. The corresponding flow curvatures and resulting centrifugal forces are also greater. The problem of theoretically determining the interference then resolves itself into the finding of the disturbance potential ϕ satisfying the Laplace Equation $\nabla^2\phi = 0$ subject to the appropriate boundary conditions discussed above. In the conventional approach to this problem for simple cases the method of images may be employed. The sketch illustrates this for the tunnel with circular cross section:

The correction to the angle of attack works out to be

$$\alpha - \alpha_{Tunnel} = \Delta\alpha = \delta \frac{S}{A} C_L$$

where S = Wing Area

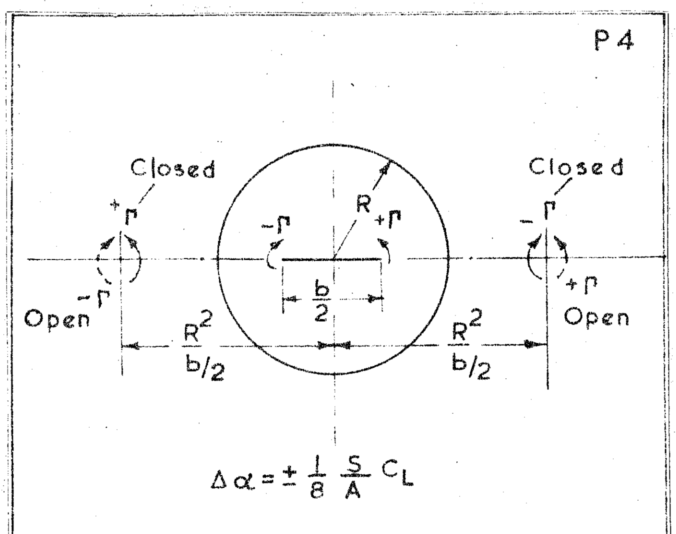
A = Tunnel Area

$= \frac{\pi R^2}{4}$

and C_L = Wing lift coefficient

δ = correction factor =

+ 0.125 for closed) Test Section.
- 0.125 for open)



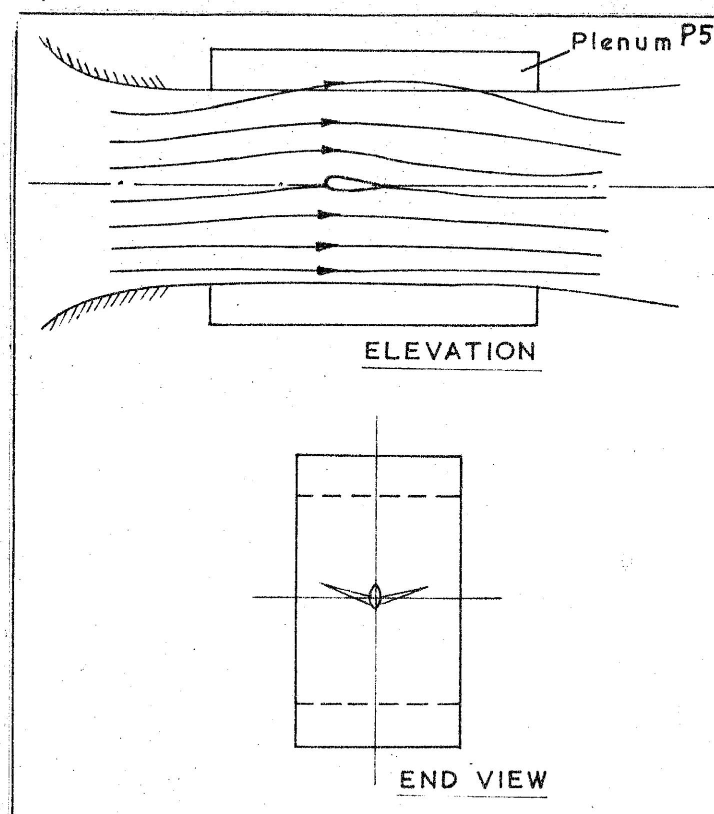
SKETCH 2

3. Flow in a Slotted Wall Test Section:

Since open and closed tunnels produce interference effects of opposite sign and nearly the same magnitude it is natural to expect that Wind Tunnels with **mixed** open and closed wall elements can be designed to eliminate the flow distortions and the interference.

Such possibilities have been studied quite long ago by Kondo (1936), Wieselberger (1942) and Riegels (1951) and some Wind Tunnels have been built on their designs. However, it was not until the advent of Transonic Wind Tunnels that the flow processes in partially open walls were studied in detail.

Consider the flow in a Test Section with longitudinal slots. The streamlines near the solid portions must follow the wall and therefore be straight while those near the open portions would curve and bulge out into the plenum chamber.



SKETCH 3

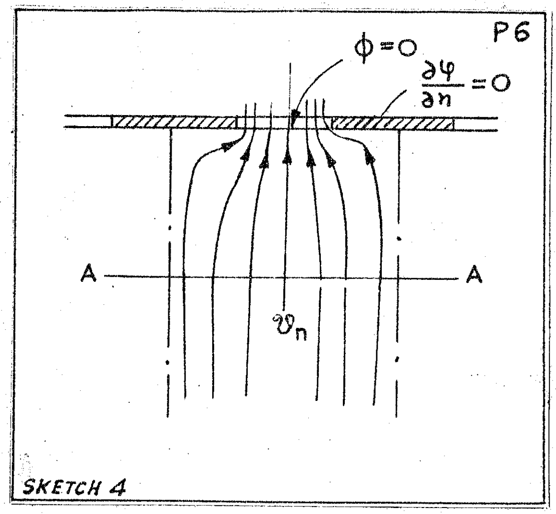
We now consider briefly the appropriate boundary conditions for this case. Recalling the linearized result for the pressure perturbation

$C_p = -\frac{2u}{U_\infty}$ we have for the disturbance pressure near the wall

$$\frac{\Delta P}{\frac{1}{2}\rho U_\infty^2} \doteq -\frac{2u}{U_\infty}$$

or $\Delta P = -\rho u U_\infty$

For the purpose of relating this pressure difference across a slot to the flow through it we now consider the flow through the slots. For simplicity we take an isolated slot and examine the flow normal to it



at the solid portion $\frac{\partial \phi}{\partial n} = 0$

At open portion $\phi = 0$ $(\frac{\partial \phi}{\partial x} = 0)$

The essential mechanism of the slotted wall is that Kinetic Energy is stored in the air which flows out of the slots and this is restored to the flow when air flows back into the tunnel. The Kinetic Energy enclosed in the region shown is

$$K.E. = \frac{1}{2} \rho \int_S \phi \frac{\partial \phi}{\partial n} \, dS$$

{ By Green's Theorem $\int_V (\nabla\phi)^2 dV = \int_S \phi \frac{\partial \phi}{\partial n} ds$

where the surface integral extends over the dotted region. Since $\phi = 0$ on open portion and $\frac{\partial \phi}{\partial n} = 0$ on walls the region near the walls contributes nothing to the integral. The problem thus resolves to finding the essentially constant potential in a plane AA. The calculation[3] is rather involved and we omit the details. The result is that the K.E. due to presence of wall is found to be

$$(K.E)_{\substack{\text{slotted}\\\text{wall}}} = \frac{1}{2} \rho V_n^2 \left[\frac{d}{\pi} \log_e \operatorname{Cosec} \frac{\pi r_o}{2} \right] \quad ; \text{ per unit wall area}$$

Refs. at end.

where V_n = local normal velocity

d = Slot spacing

δ = slot width

$r_o = \frac{\delta}{d} = \frac{\text{slot area}}{\text{Total area}}$ = open area ratio of the slotted wall

We note that the quantity $\left[\frac{d}{\pi} \log_e \operatorname{Cosec} \frac{\pi r_o}{2}\right] = \ell$ has the dimensions of a length. 'ℓ' is called the "Restriction Constant" for the slotted wall. The above Kinetic Energy is associated with the velocity v_n at a certain distance from the wall characterised by the plane AA. We now imagine that a homogeneous equivalent wall (sits at AA with the local flow) of K.E. being $\frac{1}{2} \rho V_n^2 \ell$ per unit wall area. Then we make the approximation that this K.E. at AA can be taken to be at the walls of the tunnel. The momentum associated with the Kinetic Energy $\frac{1}{2} \rho V_n^2 \ell$ is $\rho v_n \ell$ per unit area of the walls. Now the pressure difference across the walls must equal the rate of change of momentum/area associated with the slots

$$\text{i.e.} \quad \Delta P = \frac{D}{Dt} (\rho \ell v_n) \qquad \left\{ \quad \frac{D}{Dt} = \text{substantial derivative} \right.$$

$$= \frac{\partial}{\partial t} + U_\infty \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}$$

For steady flow $\frac{\partial}{\partial t} \equiv 0$ and for fixed slots and derivatives in other directions than x to be negligible we get

$$\Delta P \doteq \rho U_\infty \frac{\partial}{\partial x} (\ell v_n)$$

and since we already have $\Delta P \doteq -\rho u U$

Equating the two expressions for ΔP we get

$$-u = \frac{\partial}{\partial x} (\ell v_n)$$

and since $v_n = \frac{\partial \phi}{\partial n}$, $u = \frac{\partial \phi}{\partial x}$

ℓ = constant

We get $\frac{\partial \phi}{\partial x} + \ell \frac{\partial^2 \phi}{\partial x \partial n} = 0$ on walls.

or integrating in X direction along the wall.

$$\phi + \ell \frac{\partial \phi}{\partial n} \quad \text{const} \equiv 0$$ as disturbances must vanish at ∞

This is the homogenized wall boundary condition which must be satisfied everywhere on the slotted wall. A similar condition can be derived for perforated walls involving their porosity characteristics. To summarize the boundary conditions for the various cases:

(a) Solid Wall $\frac{\partial \phi}{\partial n} = 0$

(b) Open jet: $\phi = 0$ or $\frac{\partial \phi}{\partial x} = 0$

(c) Slotted wall: $\phi + \ell \frac{\partial \phi}{\partial n} = 0$ or $\frac{\partial \phi}{\partial x} + \ell \frac{\partial^2 \phi}{\partial x \partial n} = 0$

$$\ell = \frac{d}{\pi} \log_e \text{Cosec} \frac{\pi r_o}{2} = f(d, r_o)$$

(d) Perforated wall $\frac{\partial \phi}{\partial x} + K \frac{\partial \phi}{\partial n} = 0$

K = function of open area ratio

= pressure drop coefficient of wall.

4. THE SOLUTION FOR INTERFERENCE OF A SLOTTED WALL CIRCULAR TEST SECTION:

Having obtained the solution for the potential for the slot flow in the simple case of a plane wall with a source also it is now easy to transform this into the problem of a circular test section by conformal transformation and find the interference velocities. It is sufficient for most cases to find the interference velocities at the centre of the wing. This works to the following expression for the interference angle

$$\Delta\alpha = \frac{1}{8} \frac{C_1-1}{C_1+1} \frac{S}{A} C_L \quad \text{where} \quad C_1 = \frac{d}{\pi R} \log_e \operatorname{Cosec} \frac{\pi r_0}{2}$$

i.e. $\frac{l}{R}$ the non-dimensional restriction constant.

& A = area of tunnel.

5. TRANSFORMATION OF ELLIPSE TO CIRCLE AND INTERFERENCE FOR AN ELLIPTIC SLOTTED TEST SECTION:

Since the practical application was to a Wind Tunnel of an Elliptic Section we now transform the solution for a circle to an ellipse. This can be done with the help of the following transformation (Fig. 1)

Let Equation of Ellipse be

$$\left(\frac{x}{\alpha}\right)^2 + \left(\frac{y}{\beta}\right)^2 = 1$$

Then the transformation which transforms the interior of this ellipse to a unit circle is

$$Z = C \operatorname{Sin} \lambda \sigma \qquad (Z \sim \text{Ellipse plane})$$

$$= m^{\frac{1}{4}} \operatorname{Sn} \sigma \qquad (\zeta \sim \text{Circle plane})$$

$$= \frac{\lambda}{2K} \text{ (Parameter)} \qquad (\sigma \sim \text{auxiliary plane}$$

where m is the squared modulus of the Jacobian Elliptic Functions whose quarter period is defined by

$$\alpha = C \cosh \frac{K'}{4K} \; ; \; \beta = C \sinh \frac{K'}{4K} ; \quad C^2 = \alpha^2 - \beta^2$$

$$K = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1-m \sin^2\theta}} \; ; \; iK' = i \int_0^{\pi/2} \frac{d\theta}{\sqrt{1-(1-m)\sin^2}} , \quad 0 \leq m \leq 1$$

This transformation allows the solution of the Elliptic test section to be derived from that of the circular tunnel by means of the relation

$$(\Delta\alpha)_{\text{Ellipse}} = (\Delta\alpha)_{\text{Circle}} \frac{d\Gamma}{dZ}$$

The final result for δ the correction factor in the formula

$$(\Delta\alpha)_{\text{Ellipse}} = \delta \frac{S}{A_{\text{ellipse}}} C_L \; , \quad S = \text{Wing Area}, \; A_e = \text{area of Ellipse} = \pi\alpha\beta$$

is

$$\delta = \left[\frac{m^{\frac{1}{2}}}{8C^2\lambda^2} \left(\frac{C_1-1}{C_1+1}\right) \left\{ 1 + \frac{s^2}{6\,C^2} \left(1 - \frac{1+m}{\lambda^2}\right) \right\} + \frac{\alpha\beta}{48C^2}\left(1 - \frac{1+m}{\lambda^2}\right) \right]$$

s = Semispan of wing

For small wings, i.e. $s \to 0$

$$\delta \simeq \frac{\alpha\beta}{48C^2} \left[1 - \frac{1+m}{\lambda^2} + \frac{6m^{\frac{1}{2}}}{\lambda^2} \frac{C_1 - 1}{C_1 + 1} \right.$$

For closed tunnel $r_o \to 0$, $C_1 \to \infty$, $\dfrac{C_1-1}{C_1+1} \longrightarrow +1$

For open jet $\quad r_o \rightarrow 1, C_1 \rightarrow 0, \frac{C_1 - 1}{C_1 + 1} \rightarrow -1$

So that

$$\delta_{\substack{\text{Closed}\\ \text{Open}}} = \frac{\alpha\beta}{48C^2}\left[1 - \frac{1+m}{\lambda^2} \pm \frac{6\,m^{\frac{1}{2}}}{\lambda^2}\right]$$

which is the same expression as obtained by classical methods. (See Milne Thomson)

6. CALCULATION OF SLOT GEOMETRY FOR ZERO INTERFERENCE:

For a given Elliptic Test Section α, β are fixed. Then knowing the ratio $\frac{\text{model span}}{\text{Tunnel span}}$, δ can be found as a function of the restriction constant C_1

$$\text{i.e.} \quad \delta = f(C_1).$$

We can thus find $(C_1)_{opt}$ for zero interference by putting $f(C_1) = 0$ and solving for C_1. Knowing $C_1 = \frac{1}{\pi}\frac{d}{R}\log_e \text{Cosec}\frac{r_o}{2}$, we can find the slot dimensions (width = δ) if we fix the number of slots. But this is all in the circle plane and we have to use the transformation again to locate the slots in the Elliptic Test Section.

The Results of such calculations for n = 2 and 4 are shown in Fig. 2 For a particular tunnel geometry with $\frac{\alpha}{\beta} = 1.5$

7. EXPERIMENTAL VERIFICATION:

Fig. 3 shows the results of tests with a finite wing in the experimental test sections with 2 and 4 slots. The experimental details were as follows:

Wing Model:

Section: NACA 65_4-021

Aspect Ratio: 3.23

Span: 9"

Chord: 3"

$\frac{\text{Model Span}}{\text{Tunnel major axis}} = 0.727$

Wind Tunnel:

1/8th scale model of H.A.L. Wind Tunnel (8.25' x 5.5' Ellipse)
$2\alpha = 12\text{-}3/8"$, $2\beta = 8\frac{1}{4}"$

Max. speed: 100 mph nominal

R.No.(for 3" chord) 2.0×10^5

2 Slot Test Section:

Open Angle (included) = 60°

4 Slot Test Section:

Slot width: 3/16"

Slot ℄ location: Symmetrical, 2.67" from vertical centre line.

The wing was also tested for the open jet and closed wall configurations. Fig. 3 shows the results. The two designs for zero interference give practically identical results which lie approximately half-way between the open and closed cases thereby confirming the negligible interference even for the relatively large model used. It is interesting and important to note that the stalling region of the lift curve is included in the region of small interference. This zone is usually difficult to obtain in usual wind tunnel tests.

8. PROBLEMS IN THE DESIGN OF WIND TUNNELS FOR TESTING OF STOL/VTOL AIRCRAFT:

The novel new conditions of test necessary to be provided in the aerodynamic investigations on STOL/VTOL Aircraft may be summarised as follows:

1. The novel forms of achieving high lift
   (a) Boundary Layer Control and Jet Flaps
   (b) Swivelling engines
   (c) Deflected slipstream or jets.
2. Abnormally high C_L's (From 3 to 15)
3. Abnormal Tunnel constraint problems
4. Separations from Tunnel walls caused by deflected jets etc.
5. Aerodynamic tests for the transition regime of flight involve low tunnel speeds (of the order of 10 - 20 ft/sec) and exceptionally uniform and smooth flow.

A detailed examination of these and other factors leads to the conclusion that low speed Wind Tunnels with a test section size of 15'x15' and capable of operation between 0-150 ft/sec would closely meet most of the requirements. An open circuit type of Wind Tunnel turns out to be the most economical and best suited for this purpose. There are however several unusual problems associated with this type of Wind Tunnel which have not received much attention so far and which need to be carefully considered. These are briefly discussed in the light of experience based on operation of the 9'x14' Wind Tunnel at the Indian Institute of Science. Two of these problems are:

(a) Necessity of provision of a long diffusor and an entrance of large contraction ratio in order to effect economy of power and low turbulence levels. Both these considerations tend to increase cost and for large Wind Tunnels can be very important. Suggested practical figures for these two items are a diffuser of 10° included angle and a contraction ratio of 10 for the contraction cone.

(b) Necessity of careful design of the entry section in order to eliminate the effect of external winds and atmospheric turbulence. An additional complication occurs on account of the sucked entry air having an inherent tendency to unsymmetric unstable motion resulting in large scale low period fluctuations in the test section at low tunnel speeds. It appears essential to have a baffle across the front of the tunnel entry and sides. The need for a properly designed honeycomb is also imperative but since this involves great cost for the sizes involved (80'x20' for the Open Circuit Wind Tunnel) simpler methods using screens and grids have to be investigated.

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R E F E R E N C E S

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4. H.Gothert: Transonic Wind Tunnel Testing (1962)

5. Milne-Thomson: Theoretical Aerodynamics, Macmillans (1948).

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Eq. of Ellipse $\left(\frac{x}{\alpha}\right)^2 + \left(\frac{y}{\beta}\right)^2 = 1$

TRANSFORMATION:

$$\left.\begin{aligned} z &= C \sin \lambda\sigma \\ \zeta &= m^{1/4}\, \mathrm{sn}\, \sigma \\ \lambda &= \frac{\pi}{2K} \end{aligned}\right\}$$

m = Squared modulus of Jacobian Elliptic functions whose quarter period is defined by

$$\alpha = C \cosh \frac{\pi K'}{4K}, \quad \beta = C \sinh \frac{\pi K'}{4K}, \quad C^2 = \alpha^2 - \beta^2$$

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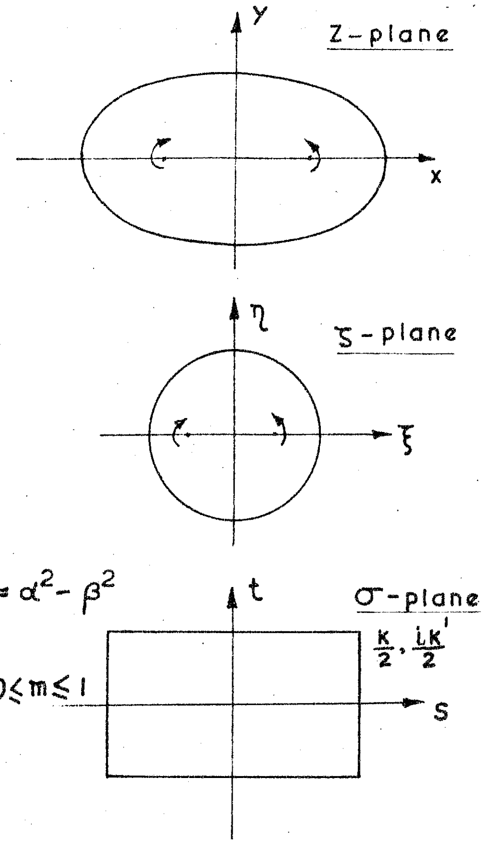


FIG. 1. MAPPING OF ELLIPSE ON A UNIT CIRCLE

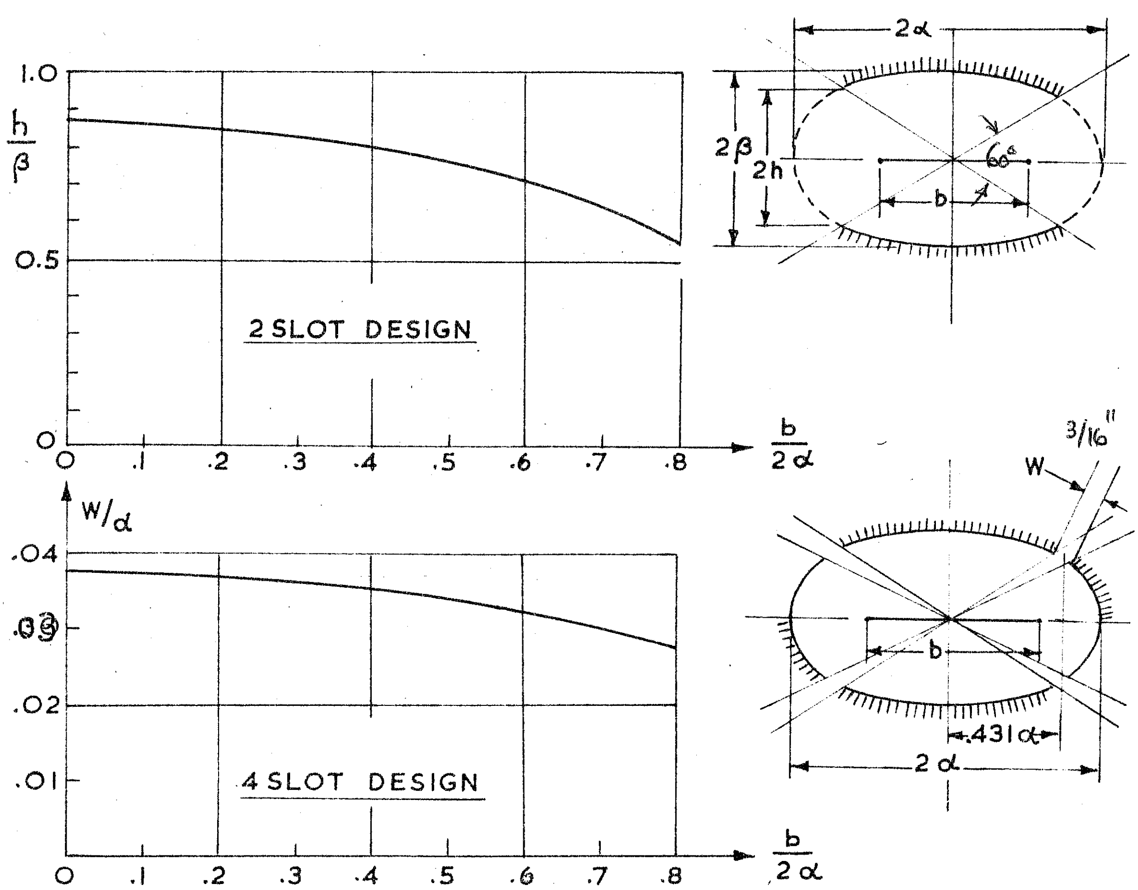


FIG. 2. ELLIPTIC TEST SECTIONS FOR ZERO INTERFERENCE $\frac{\alpha}{\beta} = 1.5$

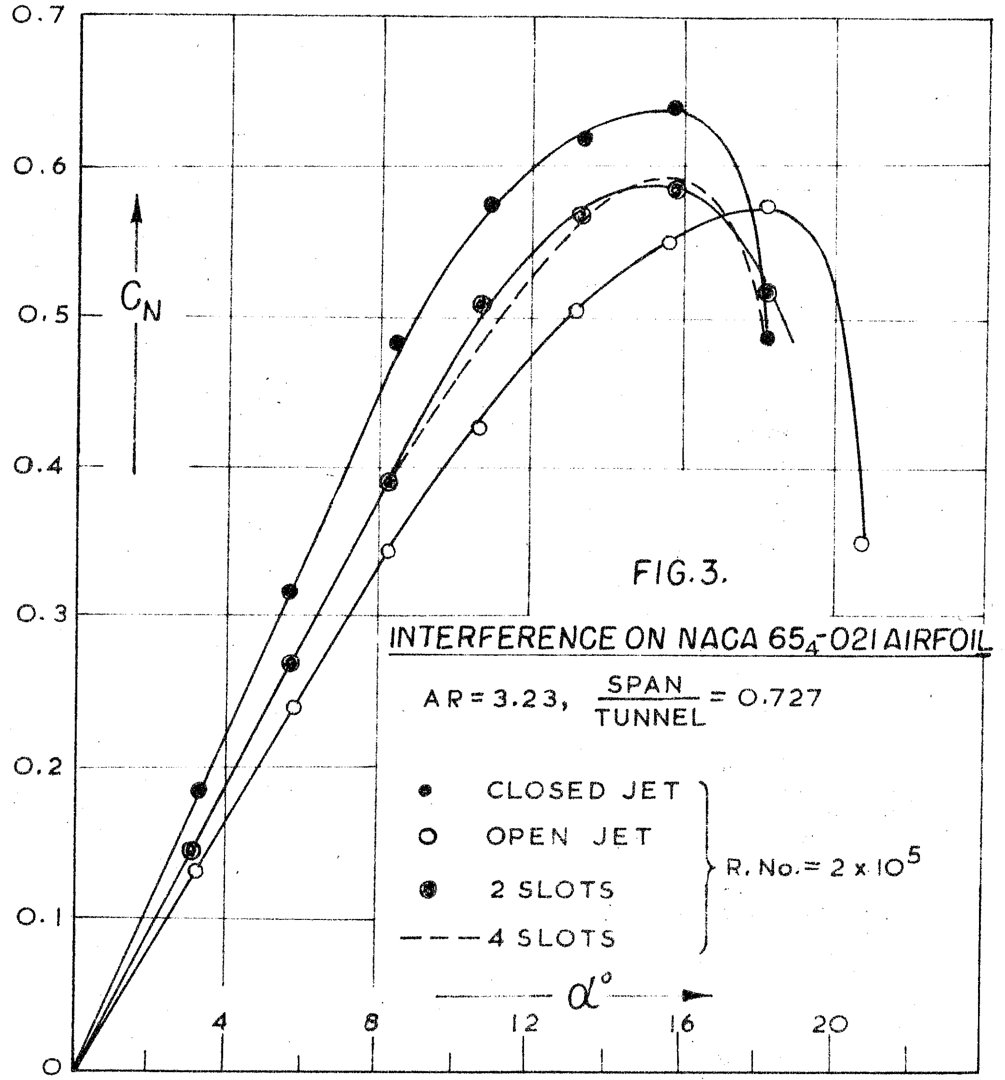
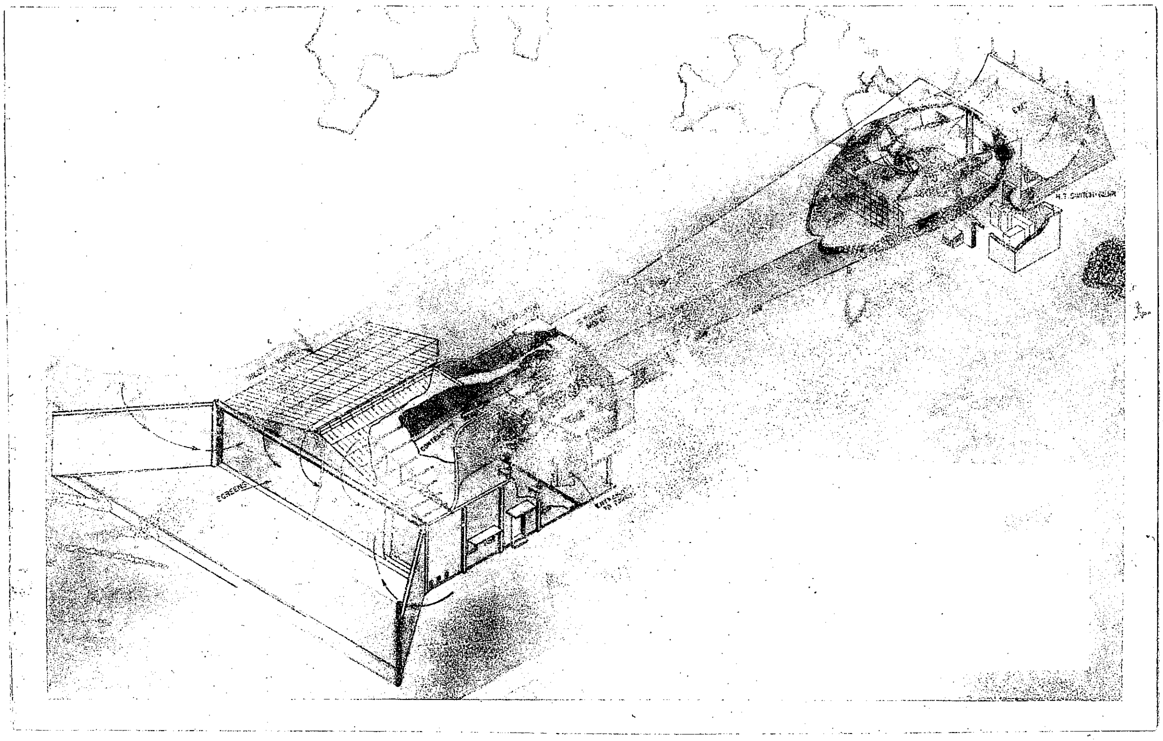


FIG. 3.

INTERFERENCE ON NACA 65_4-021 AIRFOIL

AR = 3.23, $\frac{\text{SPAN}}{\text{TUNNEL}} = 0.727$


H.T. SWITCHGEAR
SCREENS

Eq. of Ellipse $\left(\frac{x}{\alpha}\right)^2 + \left(\frac{y}{\beta}\right)^2 = 1$

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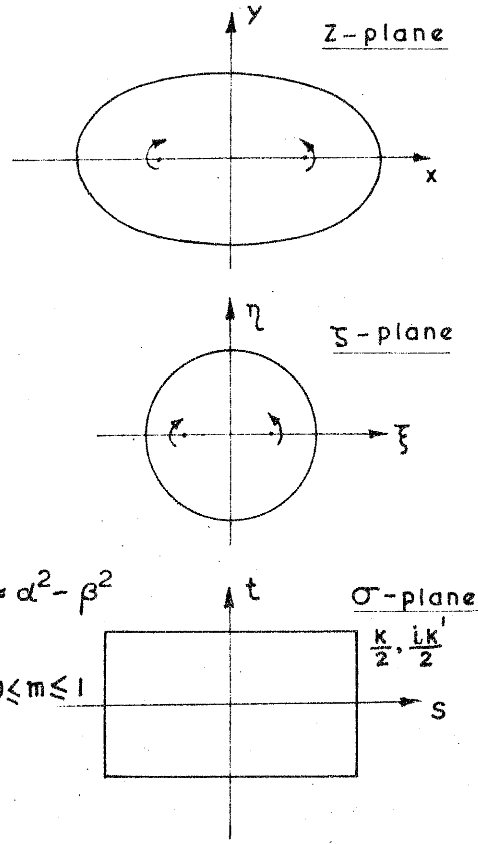

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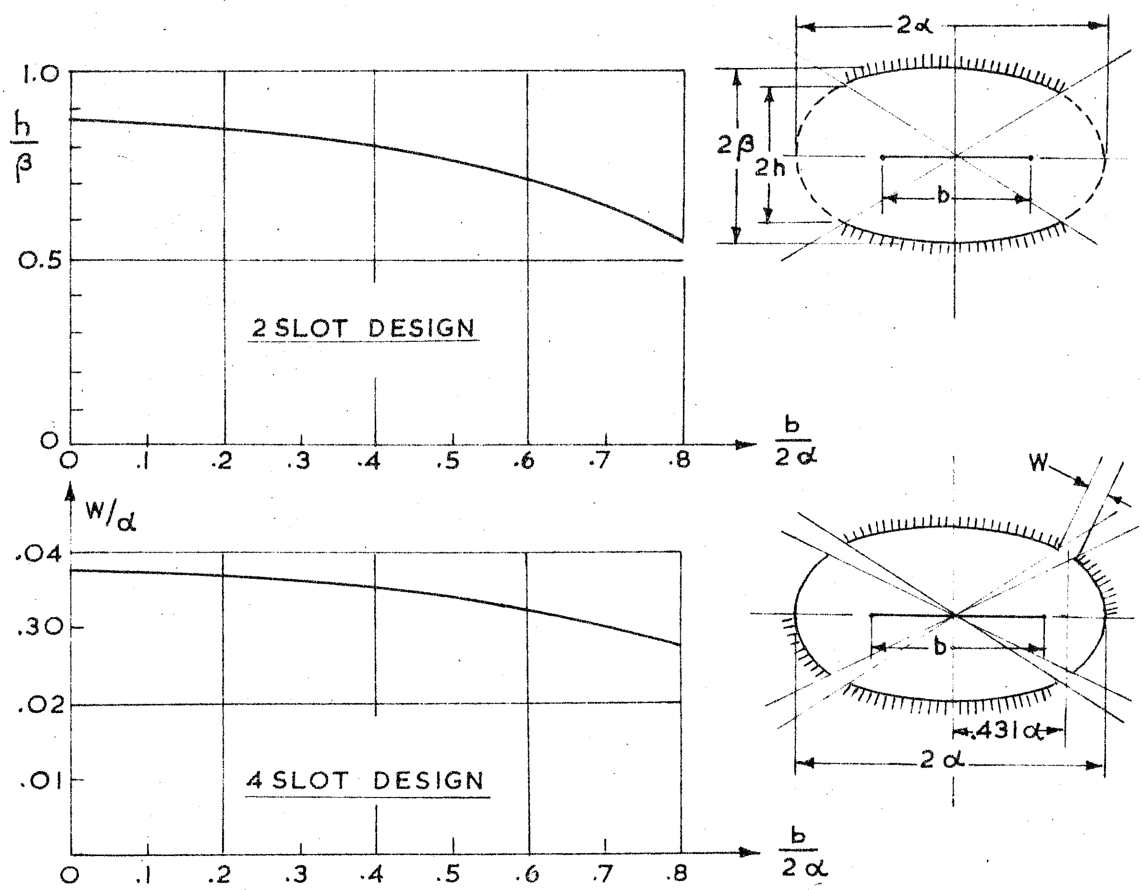

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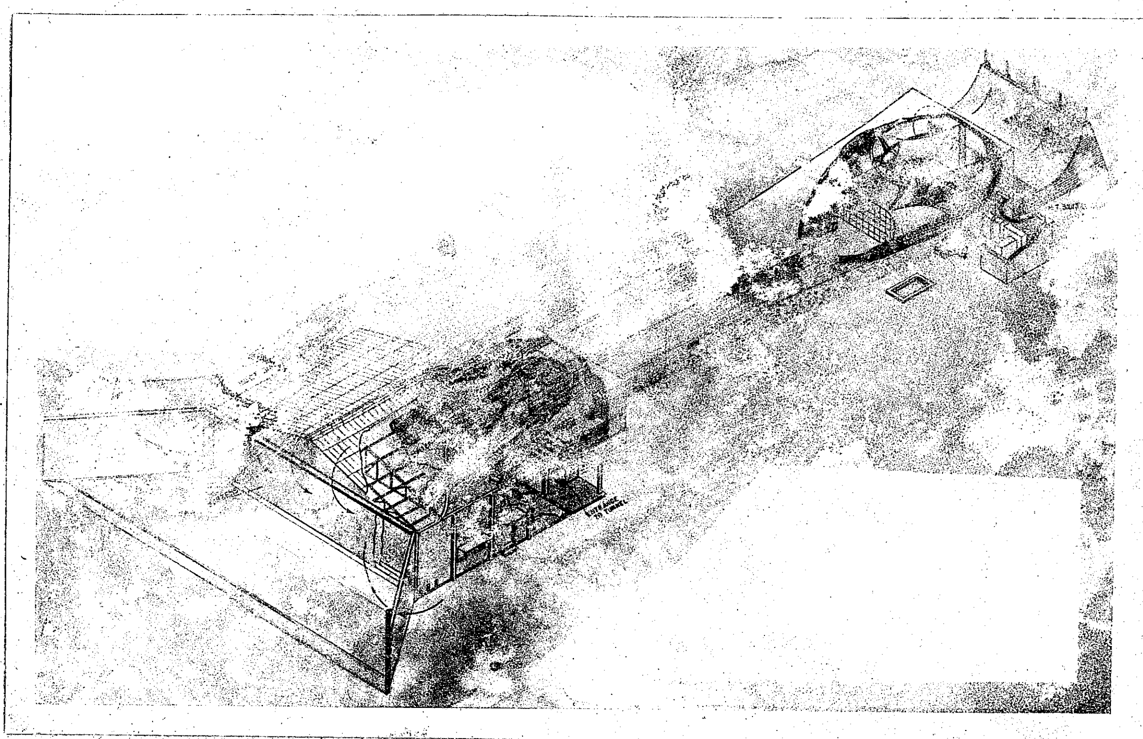
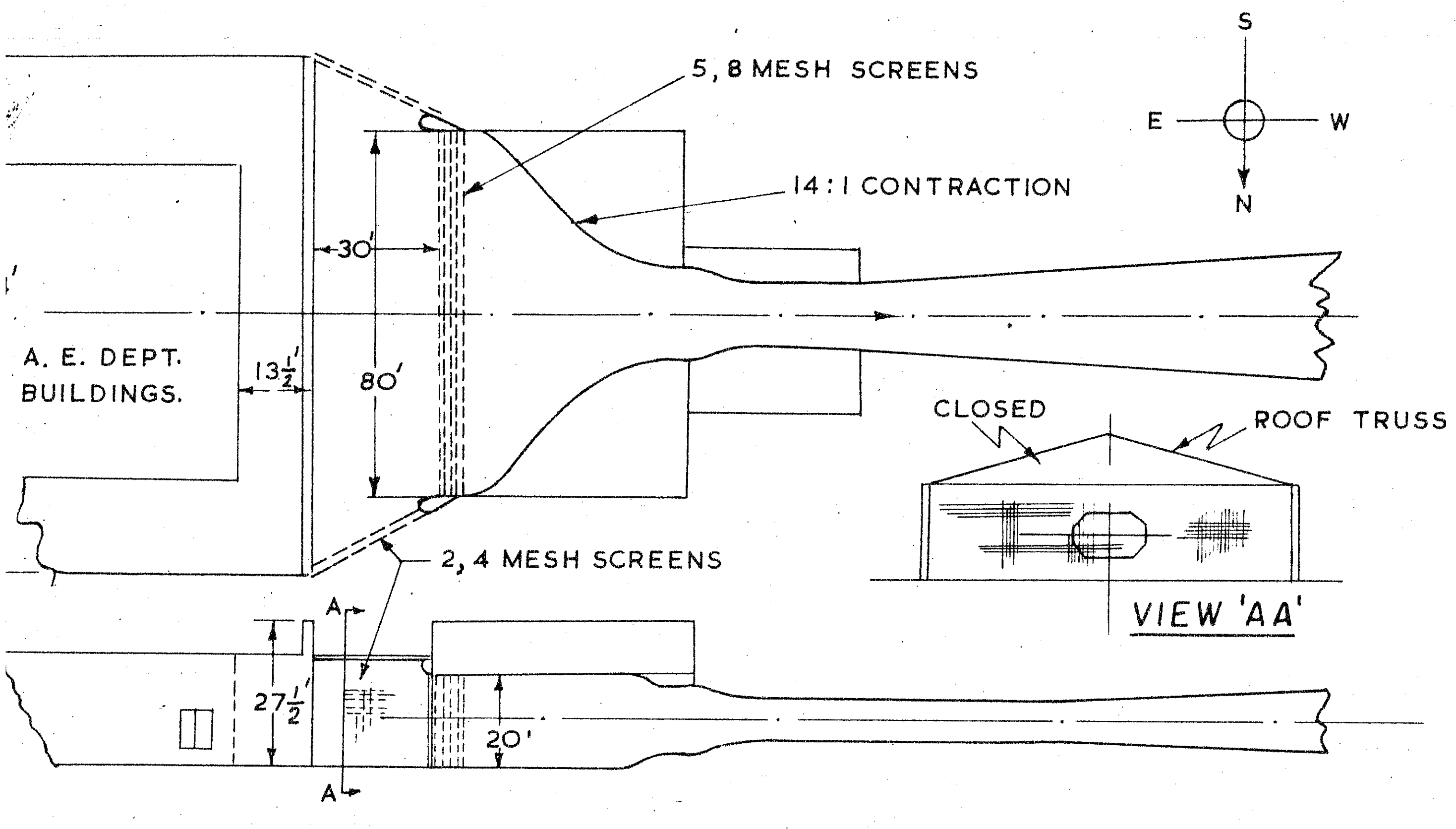




LAY-OUT OF ENTRANCE ZONE OF 9'X14' OPEN CIRCUIT WIND TUNNEL

FIG. 1.

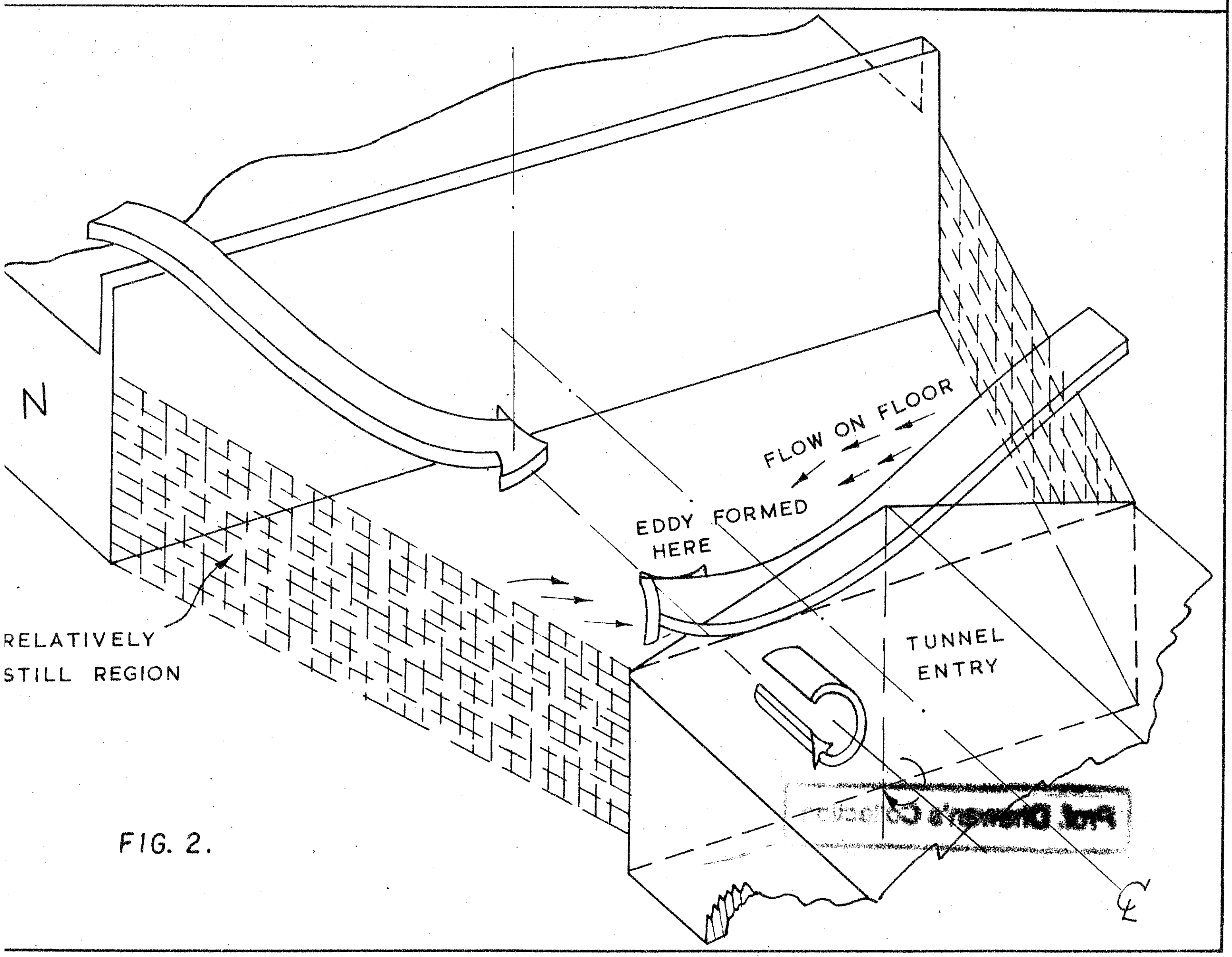
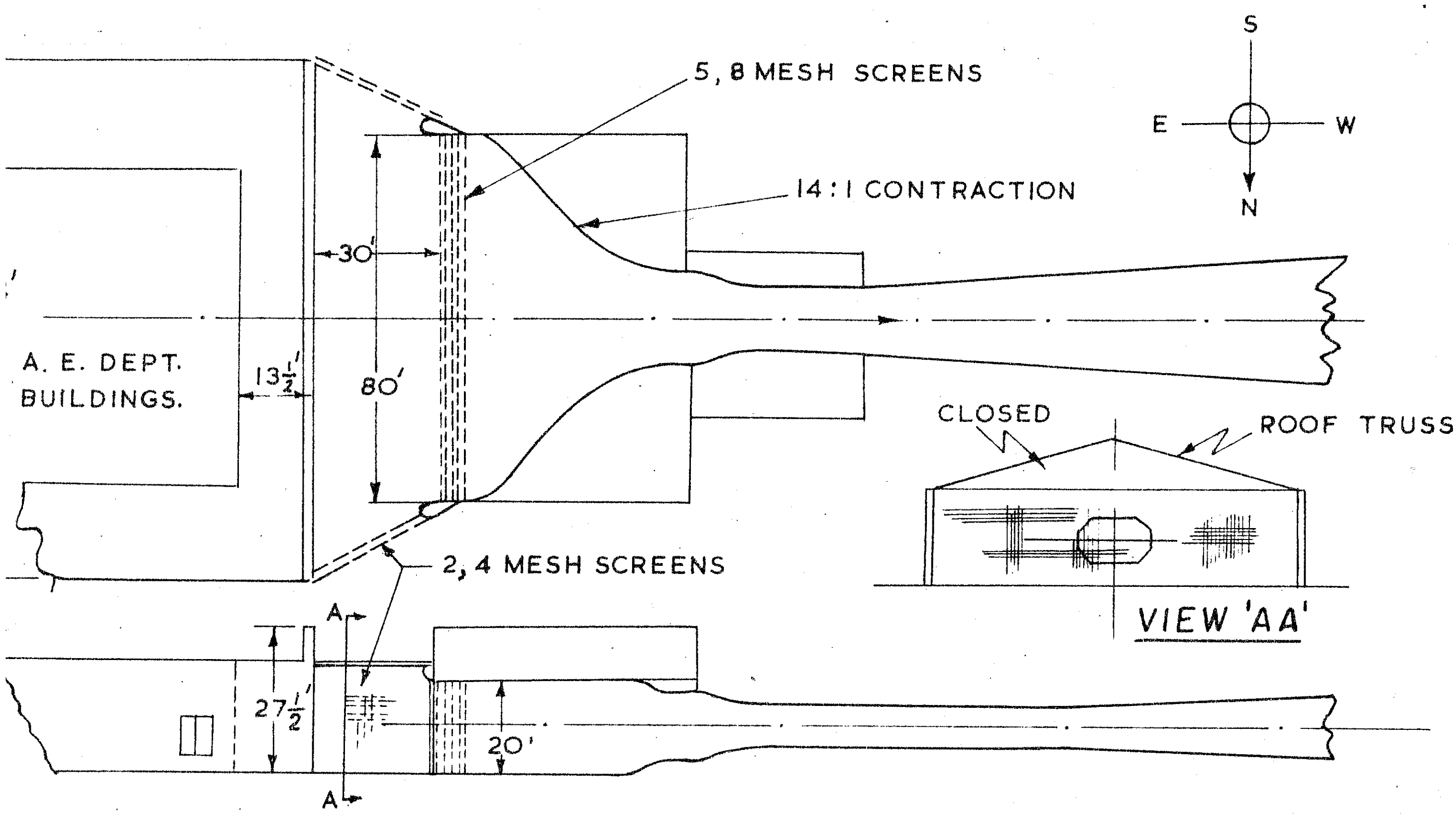


FIG. 2.



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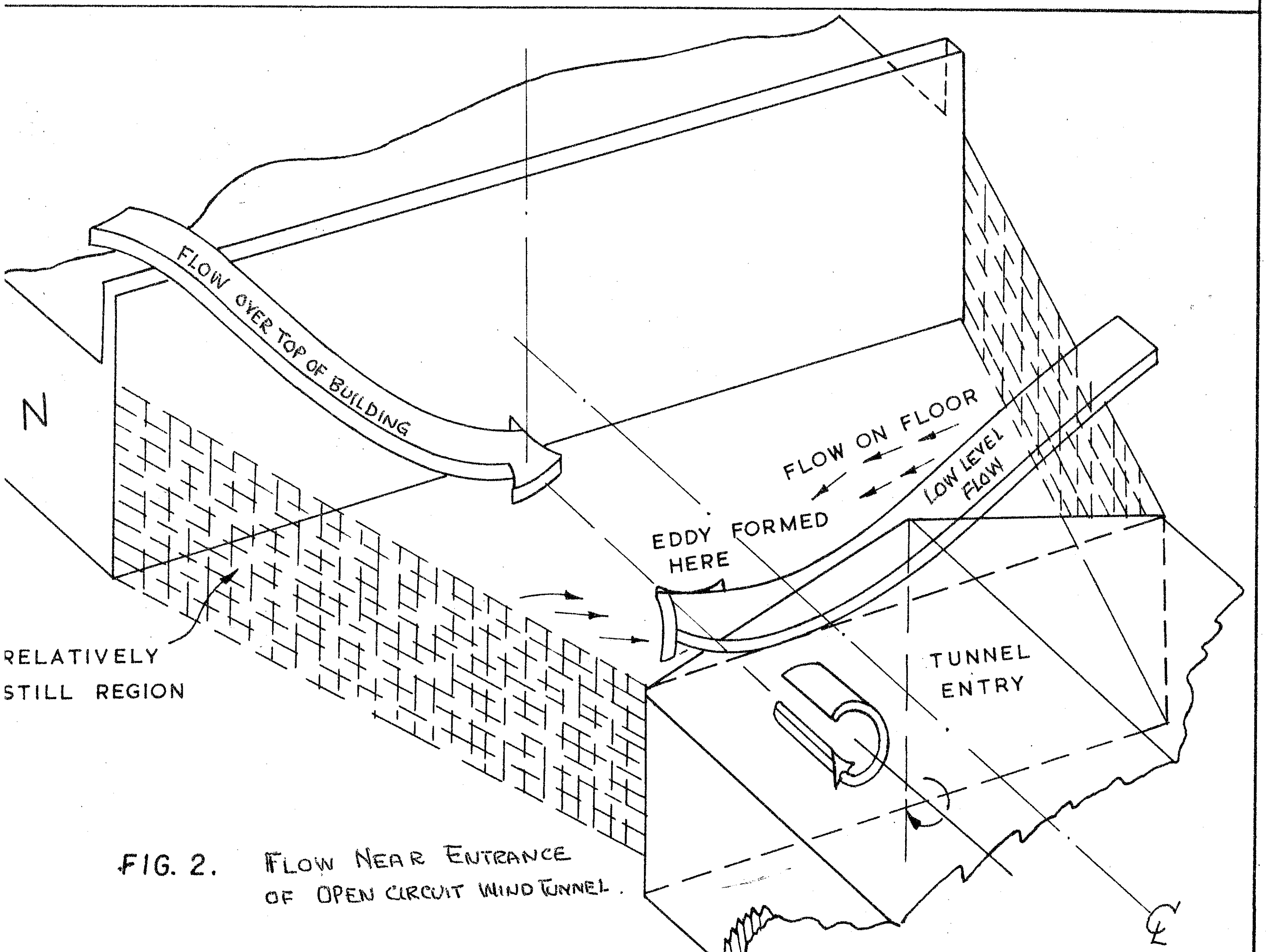

FIG. 2. FLOW NEAR ENTRANCE OF OPEN CIRCUIT WIND TUNNEL.

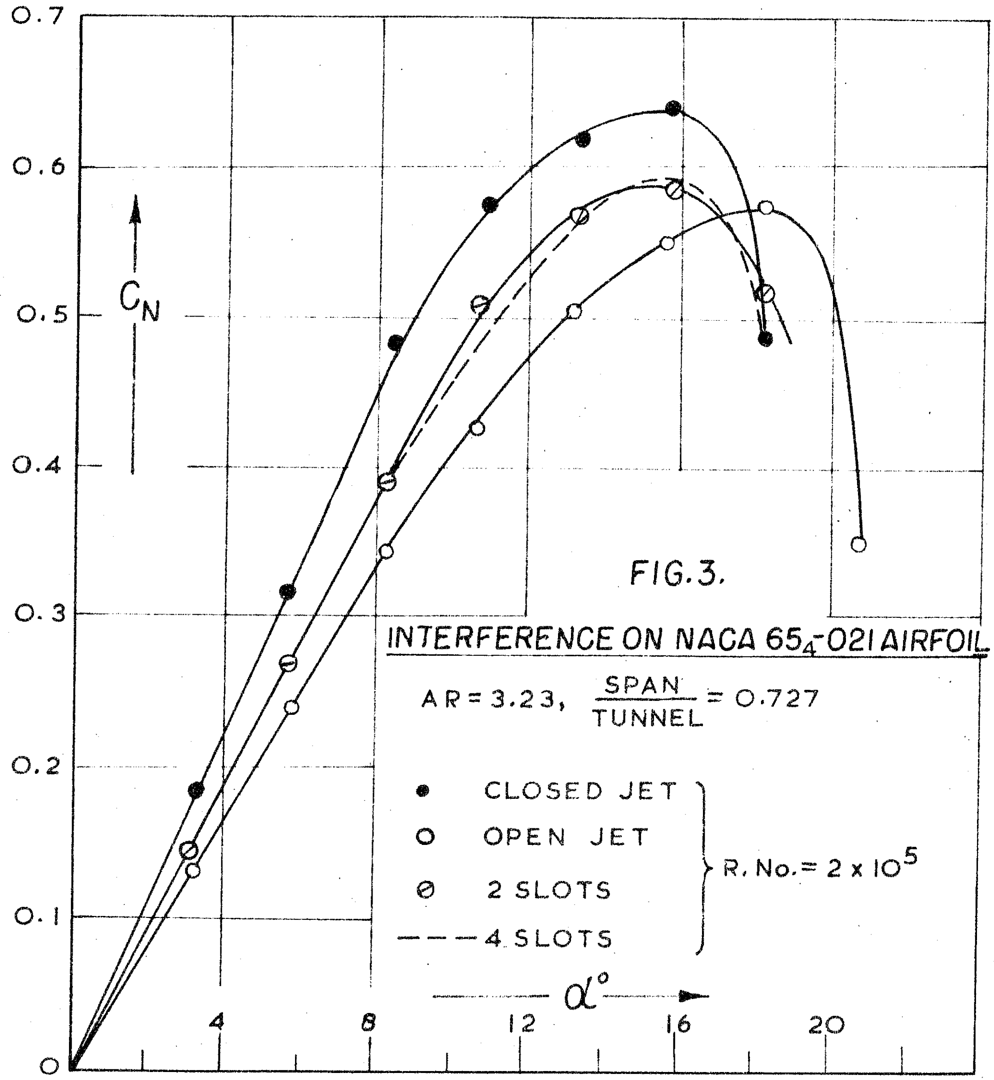

FIG. 3.

INTERFERENCE ON NACA 65_4-021 AIRFOIL