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THE INFLUENCE OF AN INCLINED JET ON THE FLOW FIELD IN THE VICINITY OF A LIFTING SURFACE AND ON ITS AERODYNAMIC COEFFICIENTS
PART II: LITERATURE SURVEY

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M. Seidel

I. Introduction

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Wind tunnel experiments and practical experience in flight have shown that new aerodynamic problems can occur in a design of VTOL aircraft. These problems involve additional flows which influence the undisturbed flow around the fuselage. These additional flows come from the engine jets. These effects, which are called jet interference effects, can have a detrimental influence on the lift of the wing or on the flow around the lifting surface. This can then influence the stability of the aircraft. These effects become more intensive and more complex the greater the inclination of the engine jets with respect to the incident flow direction of the aircraft (extreme case of vertical lifting jet). This can be seen in Figure 1. In addition, there is a considerable influence of the location of the jet nozzles with respect to the lifting surface and the ratio between the jet velocity and the flight velocity. Up to the

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

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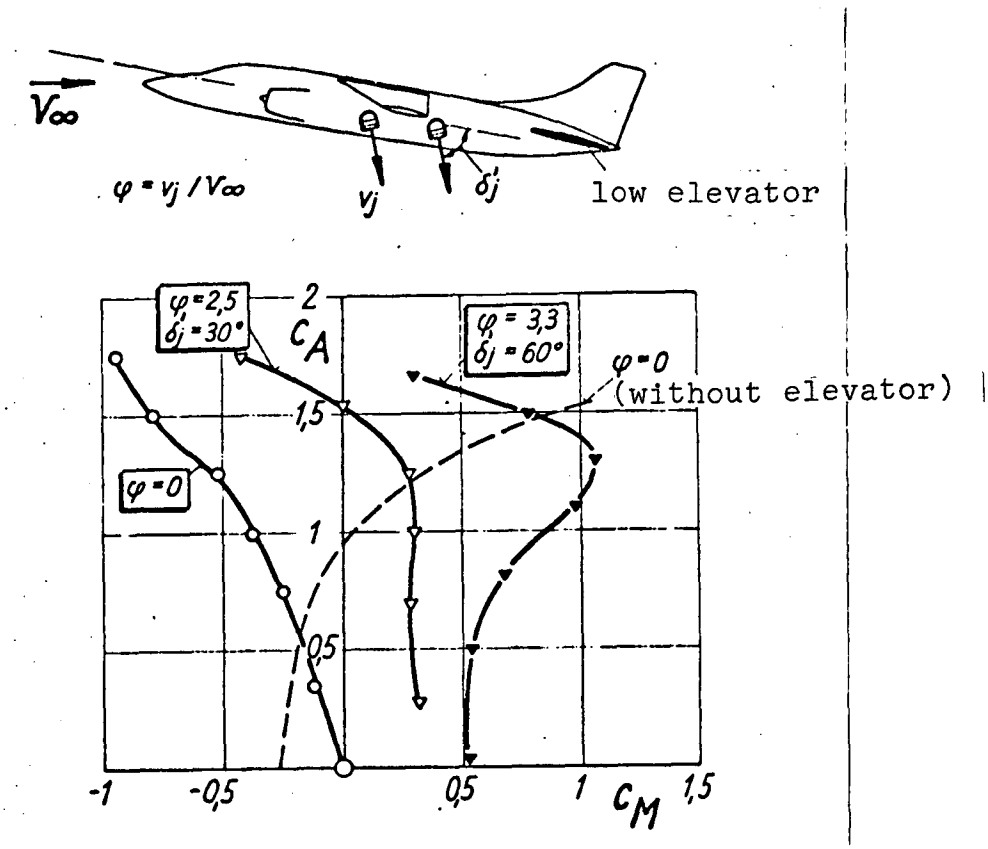

Figure 1. Spatial influence of engine jets on the longitudinal stability of an aircraft; according to [3].

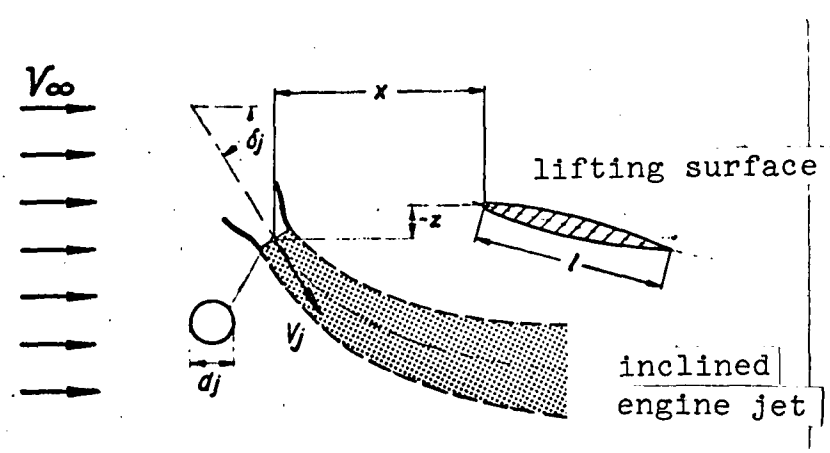

Figure 2. Notation and principal arrangement of the engine jet and the lift producing body.

present, this has not been analyzed theoretically. In [1] such jet problems were briefly discussed, in particular, the vertical take-off aircraft.

A systematic study on the propagation of inclined engine jets and their influence on the flow around lifting surfaces has been initiated at the Institute for Aerodynamics of the DFL. Some results were already published in a partial report [2]. The investigation concept was designed because of the large number of parameters and the extremely complicated flow conditions. We determined that only an experimental program can produce the first results on the interaction of the jet, the parallel flow and the lifting surface.

A critical survey of literature on questions of jet propagation interference was required to perform this task. The present report is a second partial report on the research project and will present this research survey. We found that there are numerous experimental papers, but only relatively few theoretical treatments of jet problems. The theoretical papers are often restricted to special cases and subjected to severe physical limitations and simplifications. This means that they have little practical meaning. The reason for this is the fact that the turbulent mixing processes in a free jet have not yet been adequately explained. Also, the mathematical difficulties are considerable.

In order to obtain an idea of the magnitude of real interference effects, it seems appropriate to first discuss various interference observations made in conjunction with special VTOL projects. (Chapter 3). The wind tunnel measurements mentioned served to clarify the phenomena only in conjunction with this basic study. The extent and importance of the results are described by a large figure appendix containing diagrams, and /4

configuration sketches.

In order to derive the laws governing interference effects, it is necessary to describe the propagation of a free jet in general. Because there is an abundance of literature on the "classical" case of a jet in a medium at rest, we will only mention a few summaries (in Chapter 4.1).

When the first jet engines were developed, a more detailed study of the free jet in a basic flow having the same direction was made. Some of the basic work is described in Chapter 4.2.

The most general and at the same time most complicated case of a jet inclined with respect to the parallel flow has been extensively studied in the last ten years, in conjunction with lifting jet technology VTOL propulsion aircraft. The main topics of theoretical and experimental papers are the determination of the course of the jet axis, the deformation of the jet cross-section and the flow fields induced by and around the jet. We attempted to give a very complete summary (Chapter 4.3) in order to carry out our own investigations.

We already discussed the difficulties, associated with the theoretical treatment of interference effects, which also explains the large number of papers. Beginning with the influence of a propeller jet on the wing and lifting surfaces, there has been a development of various lifting wing theories for inhomogeneous incident flow. However, they are restricted to the special case of an almost horizontal jet. Nevertheless, they are worth mentioning because of their analytical methods (Chapter 5).

Chapter 6 summarizes the small amount of experimental fundamental data on jet interference for lift-producing bodies,

(wings and lifting surfaces). Our own measurements are also described.

Table 1 gives a summary of the topics covered in this report. We did not consider work on the ground effect on jet propagation or work on supersonic jets. /5

This summary describes the state of the art at the middle of the year, 1967. In addition, a few more recent papers were available. Secondary literature or translations have been mentioned in some cases where it would have been difficult to obtain the original papers or where summaries with their own reference lists seemed more appropriate. Some of the references are given with their own figures according to the original papers. We used a unified notation of the variables (Fig. 2) in order to simplify comparisons.

2. Notation (See Figure 2)

2.1 Geometric variables

Symbol	Dimension	Meaning
b	m	Span of the lifting surface
d	m	Profile thickness
d_j	m	Nozzle exit diameter
$d_{je} = 2 \cdot \sqrt{F_j/\pi}$	m	Effective nozzle diameter
$F = b \cdot l$	m^2	Lifting surface area
$F_j = \frac{\pi}{4} \cdot d_j^2$	m^2	Jet cross section at the nozzle exit
l	m	Lifting surface chord
x, y, z		Cartesian coordinates (origin at the center of nozzle mouth)
x_K	m	Length of the potential core in the jet

Symbol	Dimension	Meaning
α	°	Angle of attack of lifting surface chord or fuselage reference axis with respect to incident flow direction.
α_W	°	Downwind direction / 6
γ_j	°	Jet induced inclination angle of the streamlines of basic flow.
δ_j	°	Inclination angle of the nozzle axis with respect to the parallel flow
δ_j'	°	Inclination of the nozzle axis with respect to the fuselage reference axis
ϵ_H	°	Trim angle of the lifting surface
η_H	°	Lifting surface flap deflection
η_K	°	Wing flap deflection
ζ, η, ξ	°	Coordinates of the natural jet axis system (See Fig. 22)

2.2 Aerodynamic variables

Symbol	Dimension	Meaning
a	m/s	Speed of sound
A	kp	Lift
$c_A = \frac{A}{q_\infty \cdot F}$		Lift coefficient (total)
c_a		Lift coefficient (local)
$c_M = \frac{M}{q_\infty \cdot F \cdot l}$		Pitch moment coefficient, referred to the 1/4 axis or center of gravity for the aircraft.

Symbol	Dimension	Meaning
M	kpm	Pitch moment
$M_j = \frac{v_j}{a_j}$		Mach number of the jet at nozzle mouth
$M_\infty = \frac{V_\infty}{a_\infty}$		Mach number of the free flow
p	kp/m^2	Static pressure
p_t	kp/m^2	Total pressure /7
q_H	kp/m^2	Stagnation pressure at position of lifting surface
$q_j = \frac{\varrho_j}{2} \cdot v_j^2$	kp/m^2	Stagnation pressure of the jet
$q_\infty = \frac{\varrho_\infty}{2} \cdot V_\infty^2$	kp/m^2	Stagnation pressure of parallel flow
S	kp	Thrust
T	^oK	Absolute temperature
V_∞	m/s	Velocity of the free incident flow (parallel flow)
v_j	m/s	Jet velocity at the nozzle mouth
$\bar{v}$	m/s	Jet velocity averaged over cross section
v_i	m/s	Intake velocity at jet edge
ϱ	$kp\ s^2/m^4$	Density
$\varphi = \frac{v_j}{V_\infty}$		Velocity ratio
$\varphi_e = \left[\frac{\varrho_j \cdot v_j^2}{\varrho_\infty \cdot V_\infty^2}\right]^{0,5}$		Effective velocity ratio (= momentum flux ratio)
Ψ	m^3/s	Stokes stream function

2.3 Subscripts

Symbol	Method
e	Effective
H	Lifting surface
j	Jet
∞	Free parallel flow

Abbreviations

HLW	Elevator	/ 8
VTOL	Vertical take-off and landing	
Δ	Difference quantity	

3. Interference observations during special VTOl projects.

3.1 Longitudinal stability

In most progress reports, the determination of the jet-induced lift is the most important topic in investigations of jet interference. The lift components at the wing, (near region of the jet) are primarily responsible for the effective thrust losses during hovering flight and transition flight. The lift changes at the lifting surface (far region of the jet) influence the longitudinal stability in an important way.

Figure 1 has been taken from a report taken by Campbell [3] and shows very clearly that considerable destabilizing effects can be produced by, for example, turning the engine nozzles, in addition to trim changes. The example mentioned in [4] by Seddon/ Nicholson and shown in Figure 3 for a horizontal engine jet shows that the interferences at a lifting surface located above the jet axis can be made small up to moderate angles of attack. On the other hand, according to Margason [5], the indirect

interference of vertical jets can lead to considerable stability reductions, and approximately half of these are produced by the lifting surface. As the flight velocities increase, the lifting jets are deflected such that downwind fields are propagated in the vicinity of the lifting surface. The intensity of these fields increases. Figure 5 shows the propagation of inclined engine jets to the immediate vicinity of the lifting surface.

Important systematic investigations Fütterer/Harms [6] Williams/Wood [7], Spreemann [8] and Schulz/Viehweger [9] on the influence of the nozzle deflection angle on the longitudinal stability has preceded the successful application of VTOL technology involving the rotating nozzle propulsion. These were primarily concerned with the projects P. 1127 and VAK 191-B.

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Figure 6 shows how pitch moment changes are produced by the lifting surface under the influence of jets inclined at various angles. Figure 7 shows the lift losses, which increase with deflection angle and flight velocity. These are induced by wings just above the nozzles. By varying the lifting surface elevation, it is possible to reduce or completely eliminate the destabilizing jet effects for the case shown in Figure 8. Figure 9 shows the stability criteria as a function of the flight velocity to which a few deflection angles are related. Figure 10 shows a plot of the total coefficients c_M as a function of the deflection angle δ'_j . The relationship $\delta_j = \alpha + \delta'_j$ must be remembered. Figure 11 shows stability curves for the horizontal and vertical nozzle position for slow flight. The special example shows that there is a strong stabilizing effect of the horizontal jet. A qualitative indication of the very low jet interference of the VAK 191-B for fast flight conditions ($M_\infty = 0.9$) was stated by Krenz/Barche [10],(Figure 12).

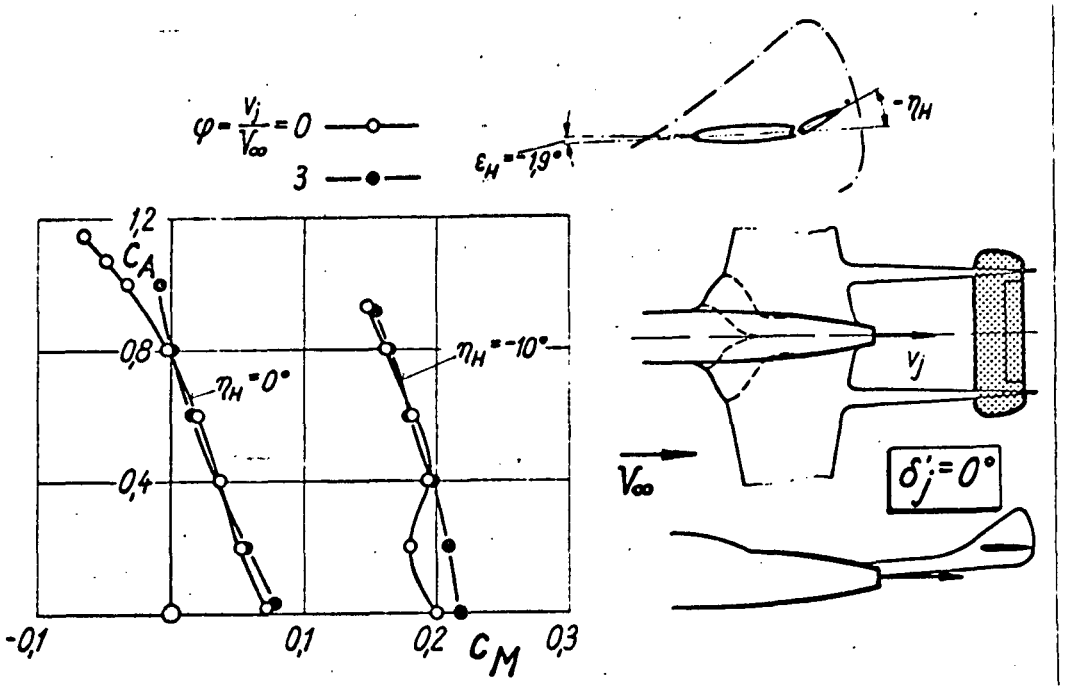


Figure 3. Influence of a horizontal engine jet on the longitudinal stability of the "vampire"; according to [4].

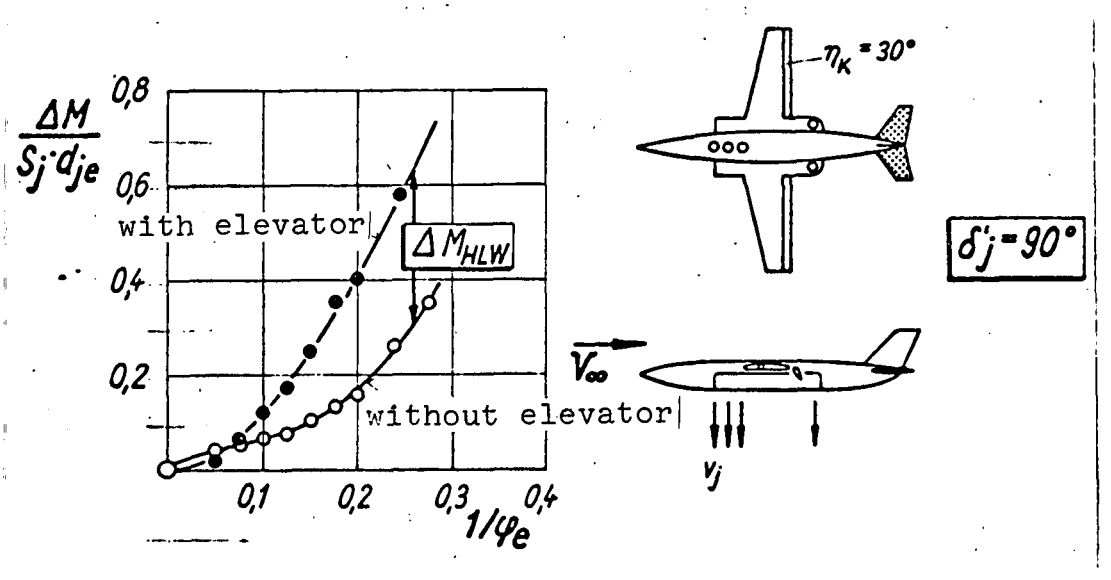


Figure 4. Influence of vertical engine jets on the elevator effectiveness of a VTOL model; according to [5].

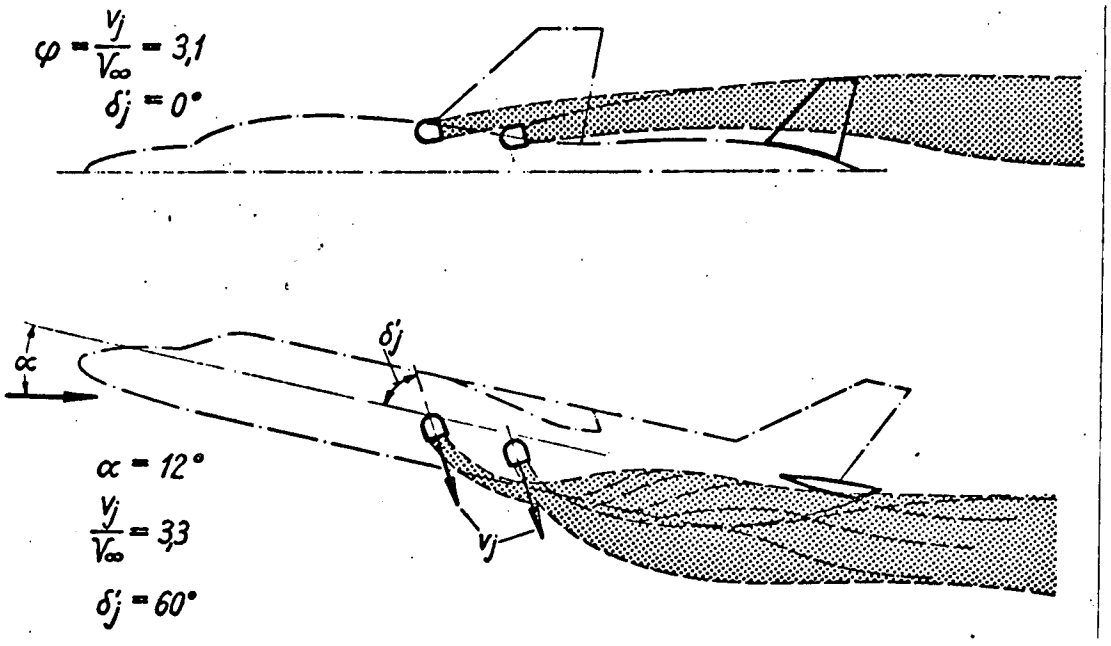


Figure 5. Propagation of cruise engine jets in the vicinity of the lifting surface. (According to smoke tunnel photographs of DFW Bremen)

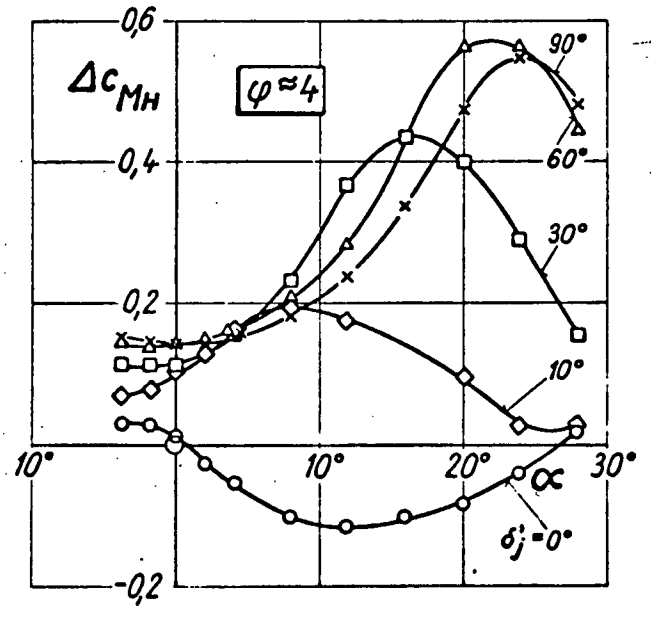


Figure 6. Change in the pitch movement because of the jet influence on the elevator of the VAK 191-B; without lifting wing, according to [6].

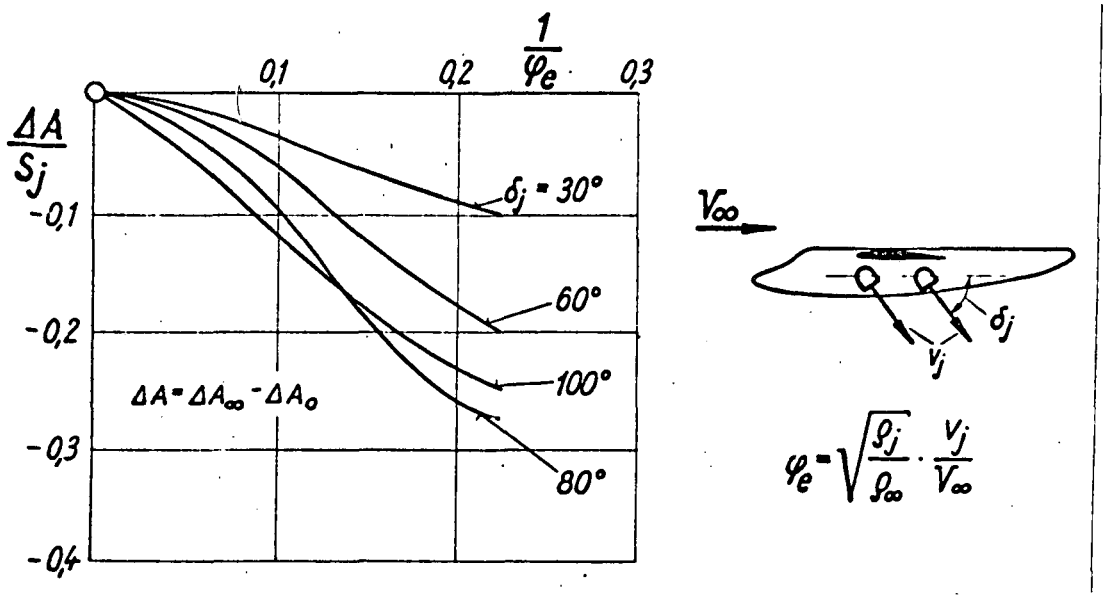


Figure 7. Jet-induced lift changes for rotatable nozzles below the wing; without lifting surface, according to [7].

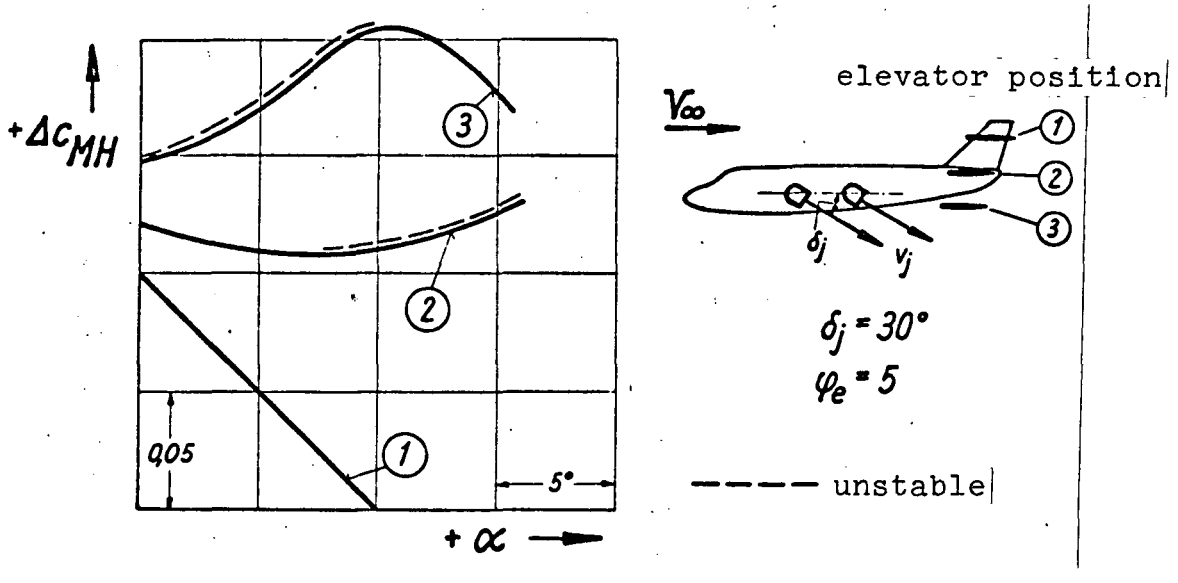


Figure 8. Influence of the elevator position on the jet induced pitch moments; without wings; according to [7].

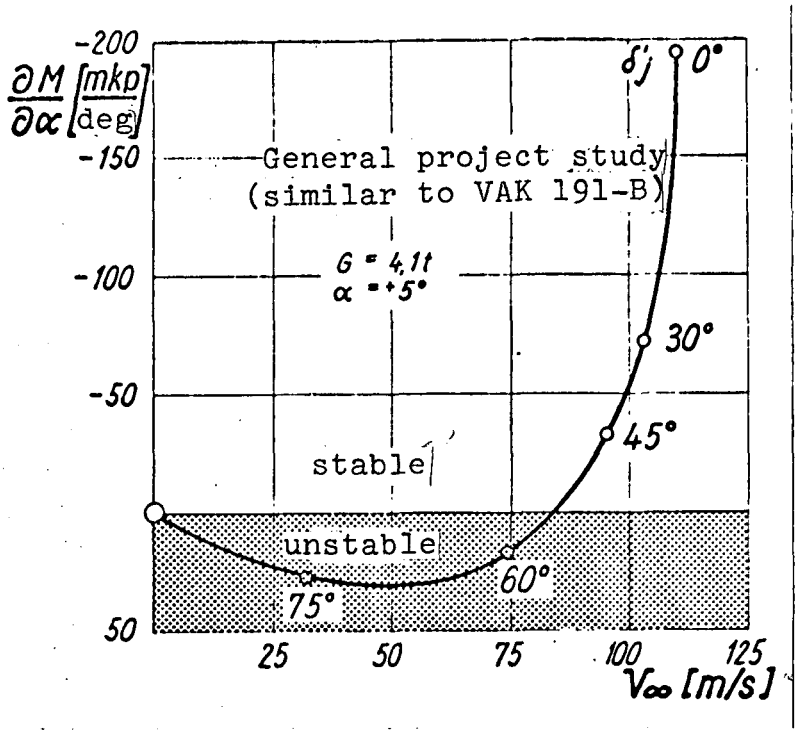


Figure 9. Longitudinal stability as a function of the deflection angle of the cruise engines; according to [8].

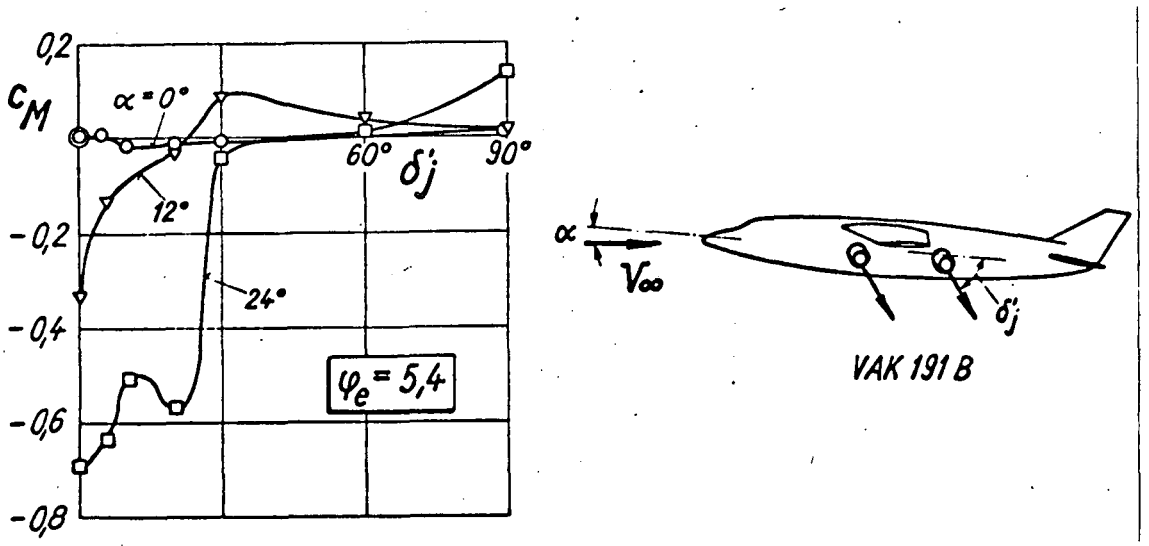


Figure 10. Pitch moment of the VAK 191-B (with wings) as a function of the deflection angle of the cruise engines; according to [9].

B

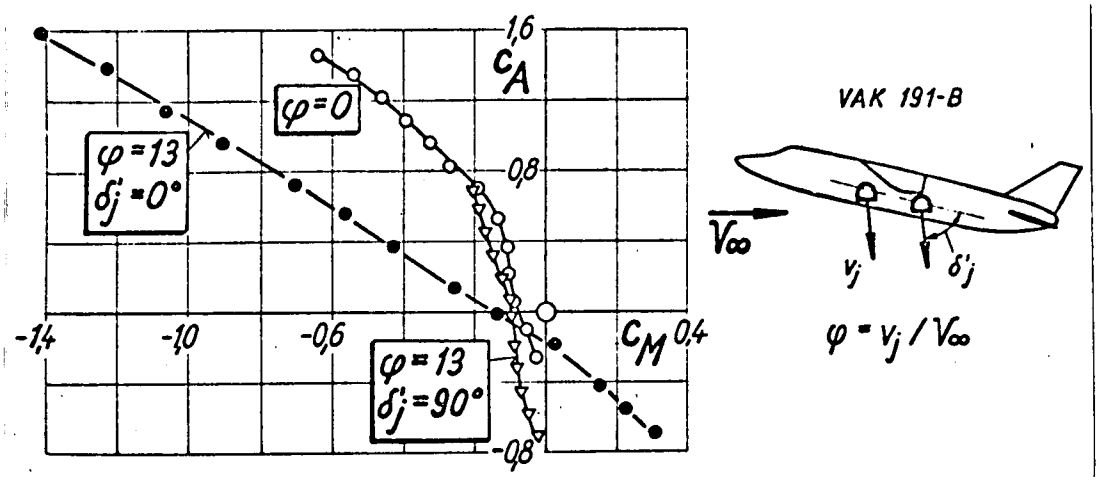


Figure 11. Influence of the cruise engine jets on the longitudinal stability for slow flight (according to [9].

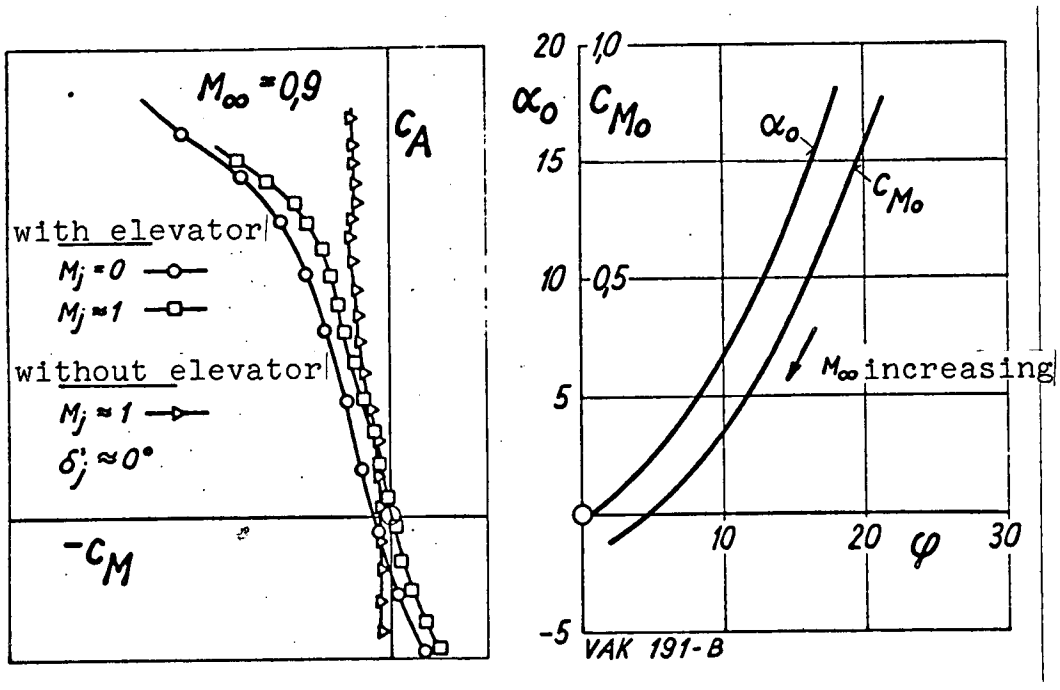


Figure 12. Influence of the cruise engine jets on the longitudinal stability for fast flight conditions; according to [10].

Scallion/Cone report in [11] on stability investigations of the influence of a jet on a tilting wing aircraft in which the jet engines are installed in the wings. A contribution of Base [12] dealt with a method of reducing interferences of engines by installing them in wings and gondolas.

3.2 Downwind at the elevator

The downwind investigations of Williams/Wood [7], Kirby [13], Squire [14] and Ribner [152 resulted in somewhat more detailed results on jet-induced flow fields over elevators, as could be obtained from overall stability analysis. Figure 13 shows stagnation ratio and downwind angle at the elevator of a tilting wing aircraft with propellor propulsion. Figure 14 shows downwind distributions over the elevator span of a tilting nozzle aircraft for two different elevator elevations. Figure 15 shows the increase in the downwind angle with jet inclination angle and with velocity ratio. Figure 16 shows a theoretical downwind distribution at the elevator. The position of the "horizontal" jet in the span direction and vertical to it was varied. The average downwind angle is related to the inclination angle of the parallel flow induced by the jet. / 10

4. Propagation of free jets

4.1 Jet with surrounding air at rest

4.1.1 Fundamentals

First we will refer to a few books which contain major contributions to the theory of turbulent free jets. In addition to the books by Birkhoff/Zarantonello [16], Pai [17] and Hinze [18], we should mention the book "Boundary Layer Theory" by Schlichting [19] which gives the theoretical foundations of jet propagation

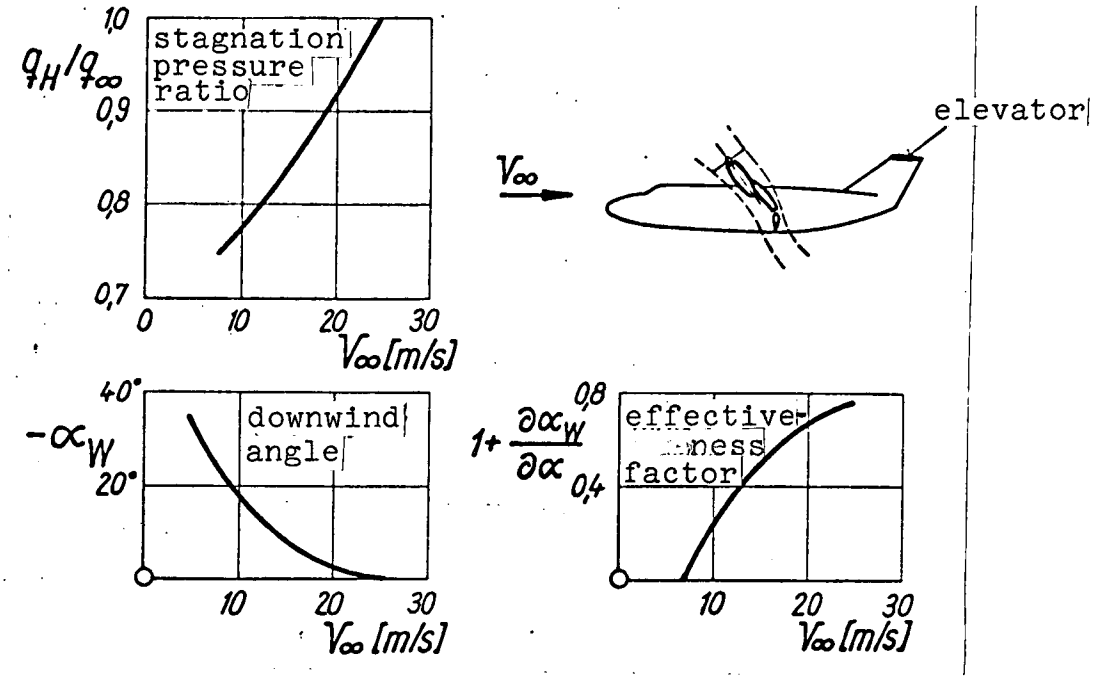


Figure 13. Influence of the screw jet on the elevator for a tip wing aircraft; according to [13].

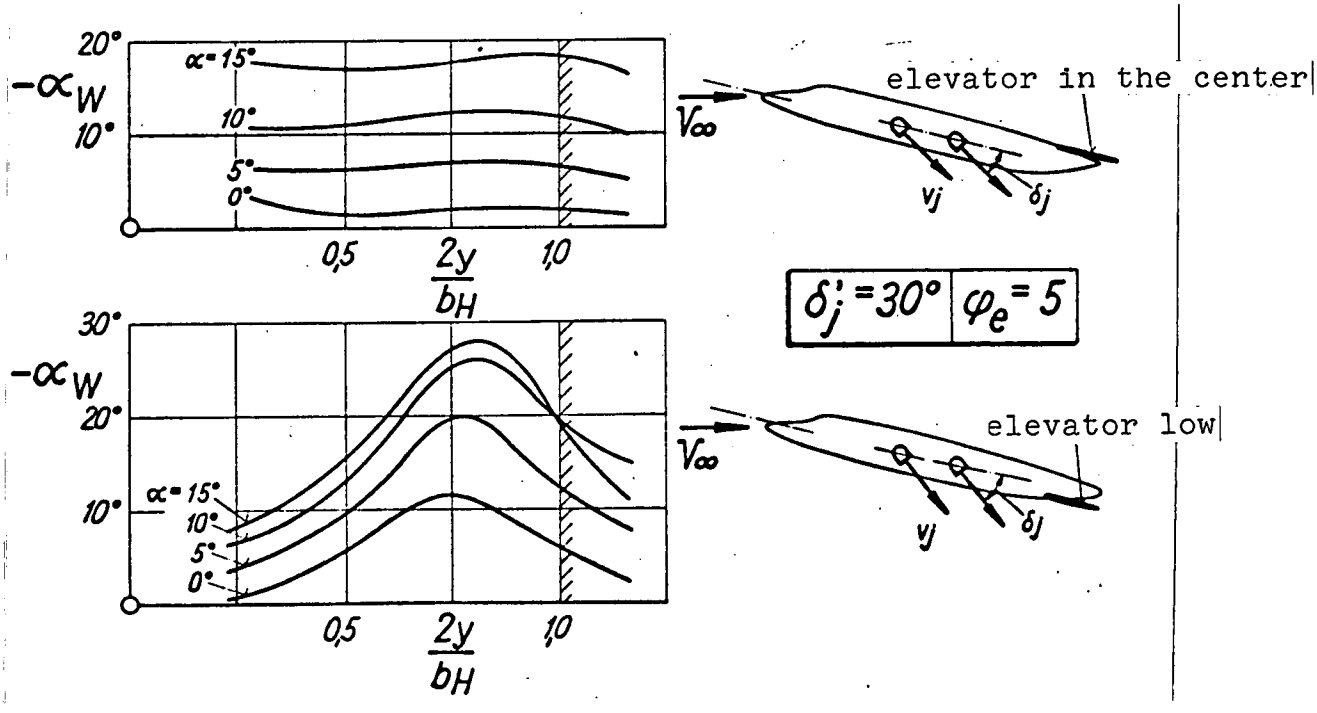


Figure 14. Influence of the engine jets on the downwind angle at the elevator; according to [7].

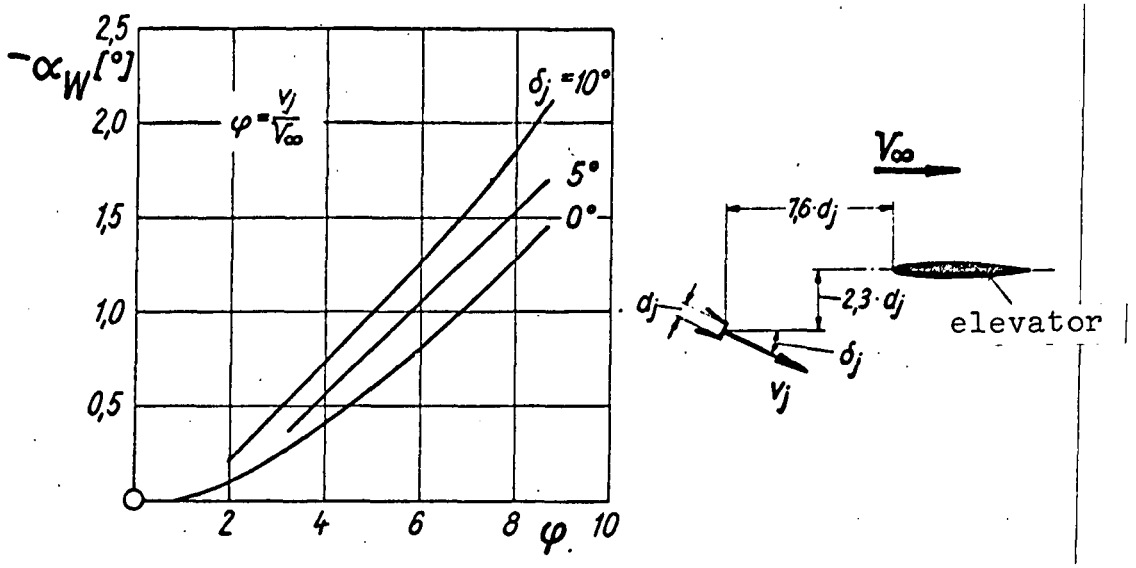


Figure 15. Influence of an inclined engine jet on the downwind angle at the elevator; according to [14].

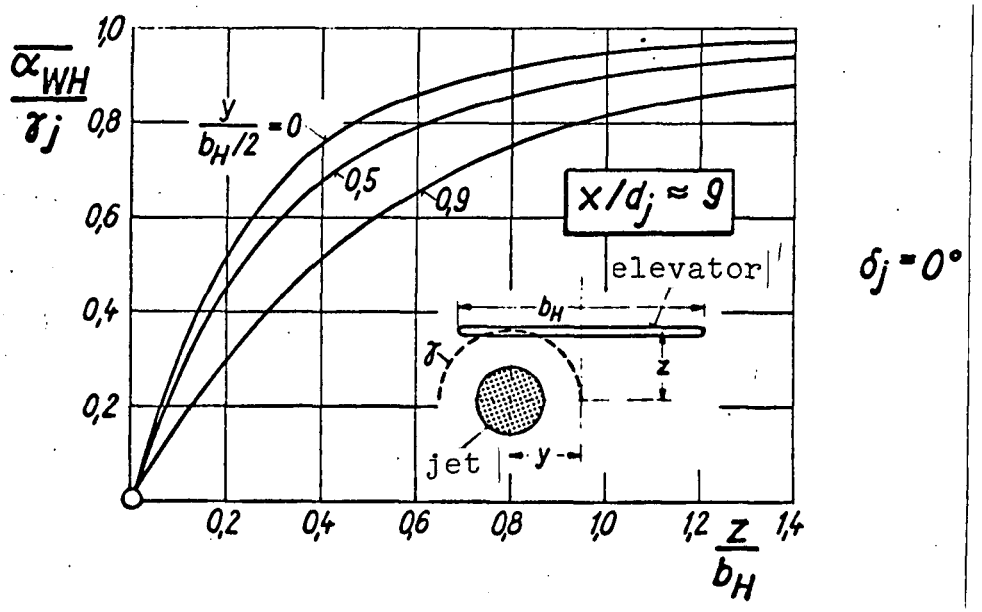


Figure 16. Average downwind angle for the elevator referred to the inclination angle γ of the streamlines at the radius z; according to [15].

in a clear way. This work was done by Tollmien, Kuethe, Förthmann, Görtler and Reichardt in the years 1926-1942. The fact that unanswered questions remain regarding the mixing mechanism at the jet boundary region, in spite of the fact that useful turbulence hypotheses have been formulated, has had a stimulating effect on jet research. An experimental contribution of Liepmann/Laufer [20] showed that neither the mixing path lengths nor the momentum transfer variables which form the basis of Tollmien and Reichardt, respectively, are constant perpendicular to the mixing region. Other important experimental investigations have been carried out by Albertson, et al. [2]] and more recently by Sforza, et al. [22] and Trentacoste/Sforza [23].

The extensive monograph of Abramovitch [24] entitled "Theory of Turbulent Jets" is a modern, standard work, which contains a large number of theoretical and experimental results. In addition, many Russian papers are published there for the first time.

4.1.2 Influence of the nozzle geometry

Comparison of experimental results is often made more difficult or impossible because no data on the exhaust conditions are given. The nozzle geometry has a significant influence on the surrounding region between the nozzle mouth and the completely turbulent jet (the so-called core zone) in which jet decay begins. Some boundary layer analyses by Wille [25] have given a partial answer to the question of how extensive an influence the flow processes in the nozzle itself have on the further jet propagation. Rajaratnam [26] points to the close relationship between the mixing processes, which primarily occur in the boundary zone of the jet, and the effective circumference of the nozzle mouth. The dependence of the length of the jet

core and the decrease in the center velocity on the nozzle geometry is shown by several examples in Figure 17. This /11 figure was taken from the work of Hammond [27], Kuhn/McKinney [28] and McLemore [29]. McKinney [30] points to the sound damping effect of star-shaped engine nozzles, which is based on extensive jet mixing just behind the nozzle and this then produces a rapid jet decay.

Additional numerical results on jet geometry and propagation can be found in Squire [14], Ribner [15], Cohen [21] and Faris [35]. Acoustic jets having an over-critical pressure ratio at the nozzle mouth differ only slightly from incompressible jets. According to Seddon/Haverty [32] the length increase of the jet core is the most pronounced effect.

4.1.3 Sink effect

When a jet is propagated, air is sucked in from the surroundings at rest into the jet. This produces an increasing volume flux downstream, coupled with a simultaneous reduction in velocity. The jet boundaries then propagate in the form of cones. The basic explanation of this phenomenon is given in Taylor [33], Ricou/Spalding [34] and Faris [35] in which the stream functions for the flow from the outside are developed and quantitative indications of the volume flux and of the velocity profiles are given.

An interesting observation has been made that there are only static underpressures in the turbulent jet regions. Recent investigations of this were made by Fiedler [36], and his paper also contains numerous references.

The sink effect is also responsible for the deformation of the flow field around the jet. Because this is the reason for many interference effects, especially for the case where the

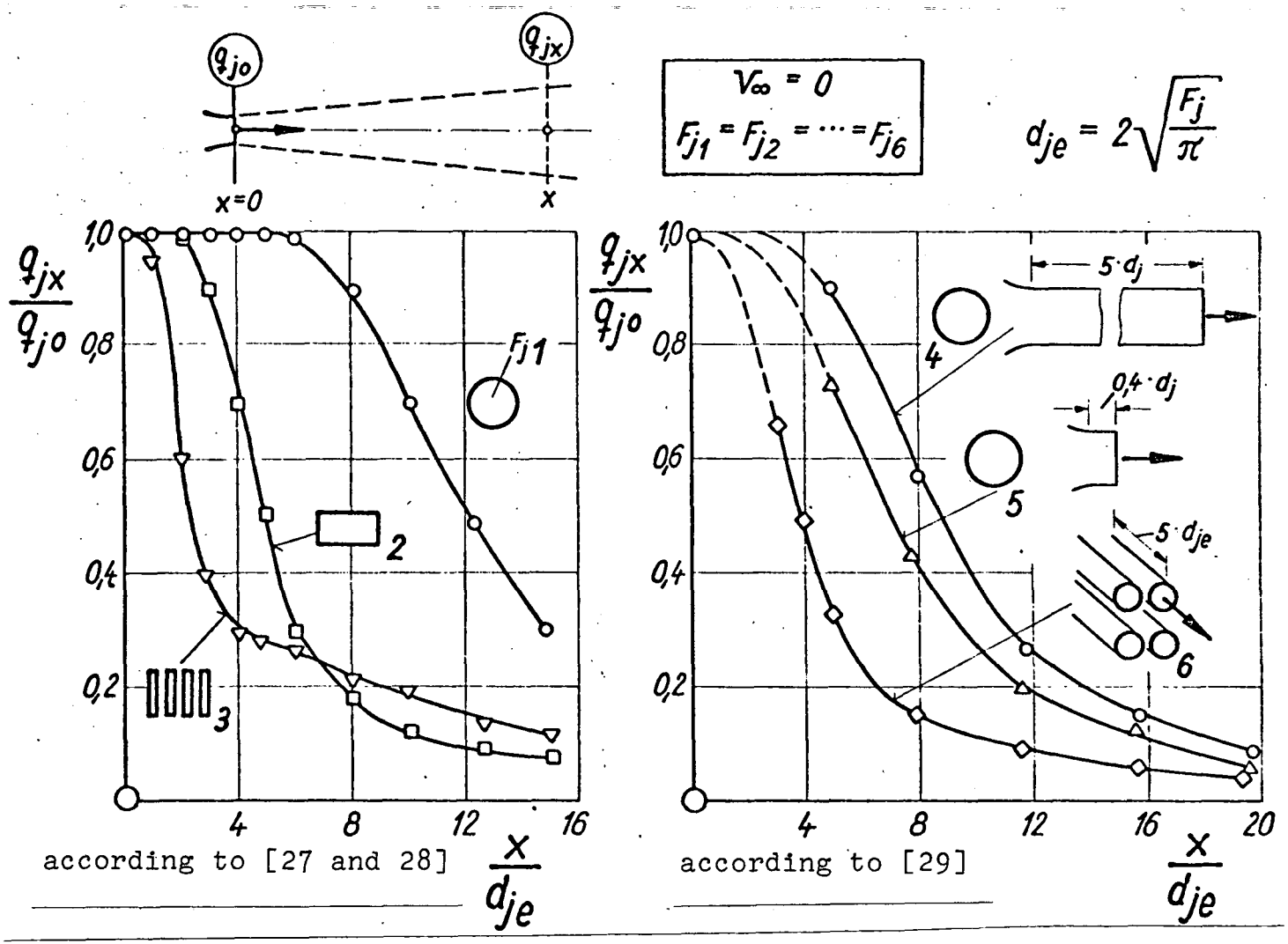


Figure 17. Influence of the nozzle geometry on the jet stagnation.

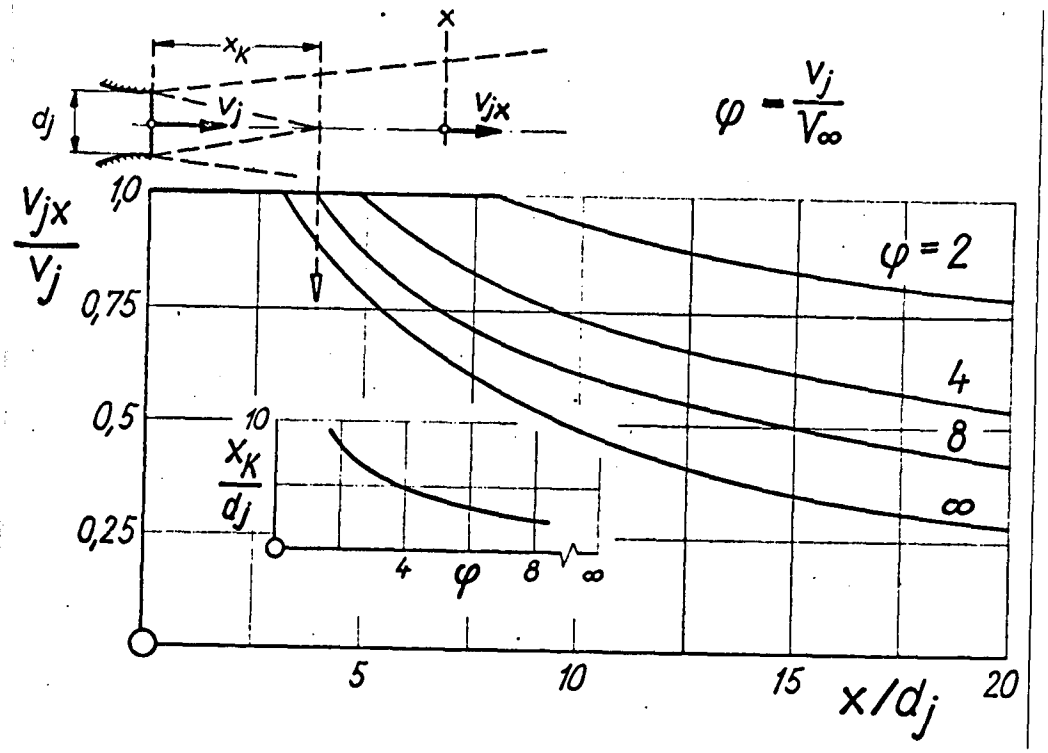


Figure 18. Influence of the velocity ratio on the velocity and length of the jet core; according to [38].

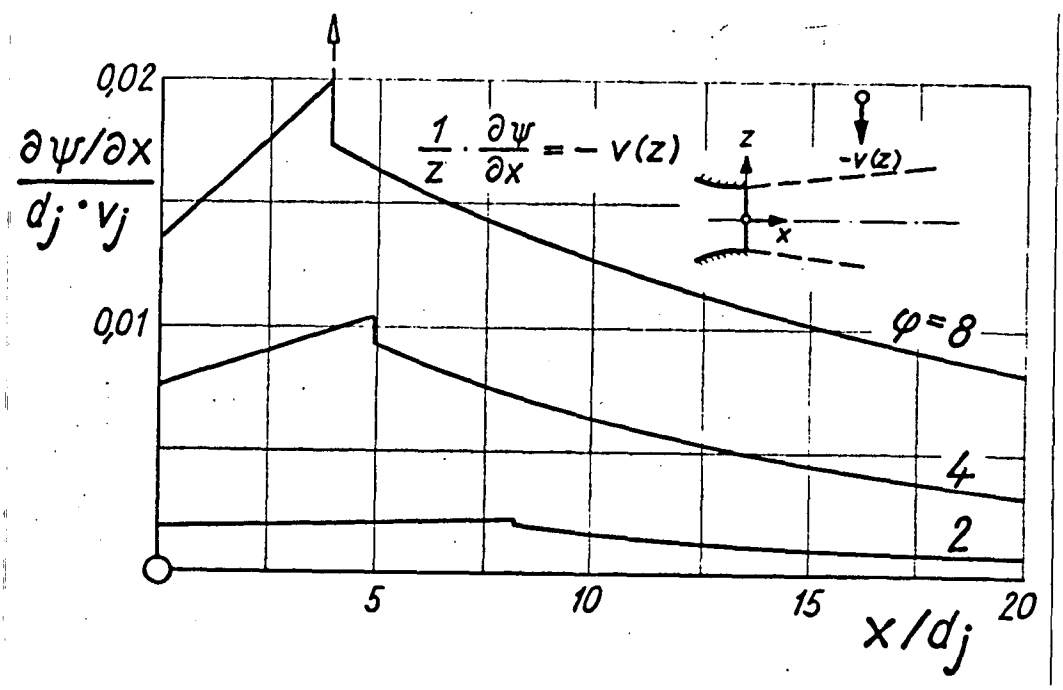


Figure 19. Sink strength of the jet; according to [38].

outer flow is in motion, we will discuss the details of this important phenomenon in the next section.

4.2 Jet in the direction of the basic flow

Papers on this topic give results regarding interference effects such as occur during cruise flight conditions because of the influence of horizontal engine jets. A bibliography of Seddon/Dyke [37] has been published and contains an extensive collection of individual references. However, it is not com- /12
plete and no longer contains important papers published after 1963.

One of the fundamental papers is due to Squire/Trouncer [38], in which the jet propagation in a parallel basic flow is analyzed theoretically using a classical shear stress trial solution. (See [19]). A mixing path parameter is derived from jet investigations for the surrounding medium at rest and in a semi-empirical way. The relatively simple theory assumes that there is a cosine distribution for the velocity profiles. The resulting axial velocities are produced by kinematic super position of the basic velocity and the jet velocity. The center velocity determined in this way and the core lengths are shown in Figure 18 for various velocity ratios, as a function of distance from the nozzle. In order to obtain results on the incoming flow induced from the outside by the jet, a sink distribution along the jet axis is derived (Fig. 19). The resulting deformation of the flow field which surrounds the jet is shown in Fig. 20. This important result to be used in interference studies was also obtained by Ribner [15] based on a careful analysis which is more refined compared with [38]. More accurate isocline figures are obtained, because measured velocity profiles were used. In addition, a relationship between the inclination angles of the streamlines

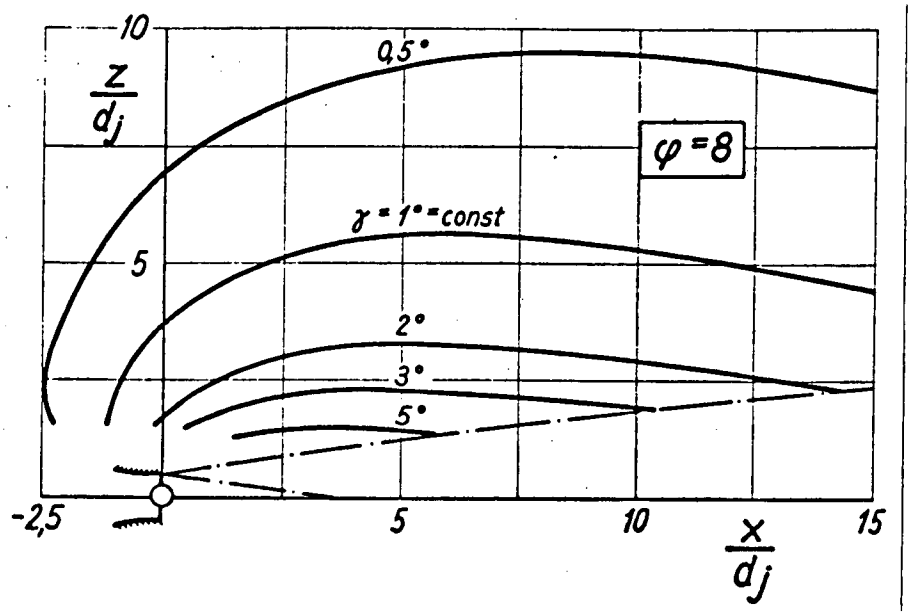


Figure 20.– Isoclines of the flow field in the vicinity of a circular jet; according to [38].

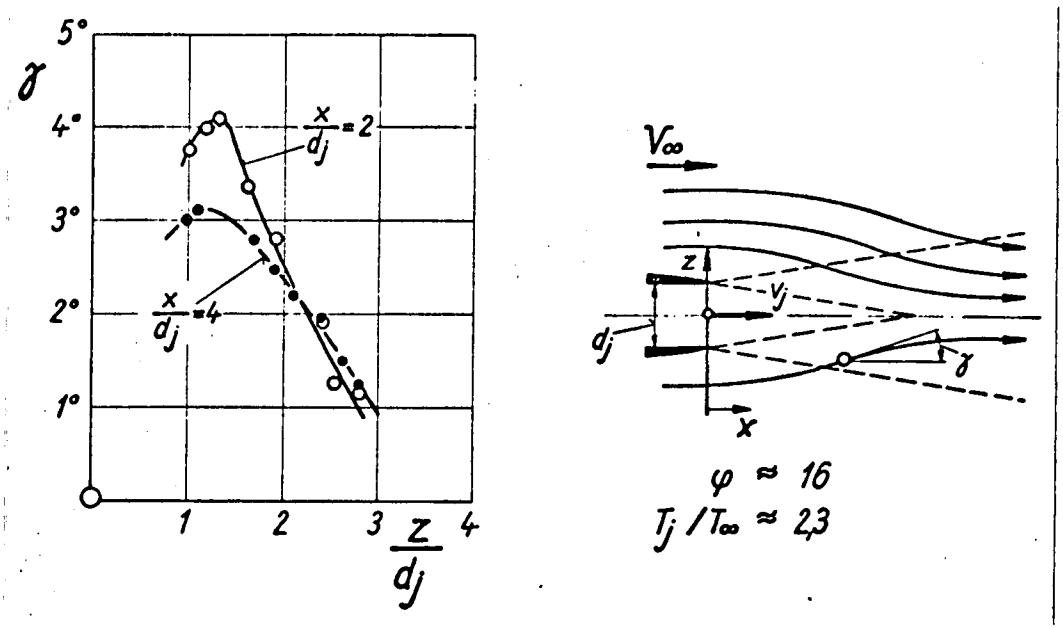


Figure 21.– Inclination angle of the streamlines in the vicinity of a circular jet; according to [44].

outside of the jet and the geometric and fluid dynamical parameters is derived. The experimentally determined inclination angles are shown in Figure 21 for a very large velocity ratio. This is taken from a paper by Pabst [44].

It is very interesting to determine the jet-induced downwind fields at an elevator and therefore the stability changes due to the influence of horizontal and slightly inclined engine jets by calculation [15]. Test results and an empirical relationship for the center velocity (as a function of the velocity ratio) are given in [14]. In addition, this paper states that the most important correlation variable is the ratio of the momentum flux density $\rho_j \cdot v_j^2$ and $\rho_\infty \cdot V_\infty^2$ of the jet or of the basic flow, (and not the ratio of the velocities v_j and V_∞).

The results discussed up to the present assumed that the mixing path parameter was known and had to be restricted within a certain range in the vicinity of the nozzle. Reichardt determined the laws for larger distances [39], [40]. The fact that no structural similarity of turbulence occurs in the range between the vicinity of the nozzle and a large distance downstream (and therefore there is no prerequisite which could be made to simplify the equations of motion) leads to the establishment of interpolation formulas for the width development of the jet. Additional results on the special features of coaxial turbulent flows can be found in Maczynski [41] and Alpinieri [42]. /13

Finally, we would like to mention the papers by Szablewski [45] which deal with variable density flows, that is, the influence of the jet temperature, for example.

4.3 Jet inclined with respect to the basic flow

Except for some earlier papers, the first investigations of this topic were stimulated by the development of engine combustion chambers. The mixing processes which occur between an air jet limited by the tube walls with fuel jets introduced from the side (usually perpendicular to the tube axis) are of interest here. When VTOL technology was introduced, a similar fluid dynamic problem was introduced into aircraft aerodynamics. This is the problem of mixing of inclined engine jets with the outer flow. Considering the direct and indirect influence of the wing and the lifting surface, it was necessary to establish the way in which the jets, which are deflected by the parallel flow, are propagated, or the specific nature of the flow fields around the free jet had to be determined. Numerous analytical and empirical solutions have been given for the first question. The second question runs into considerable theoretical difficulties, as, for example, a literature survey by Garner [46] says.

4.3.1 Theoretical work

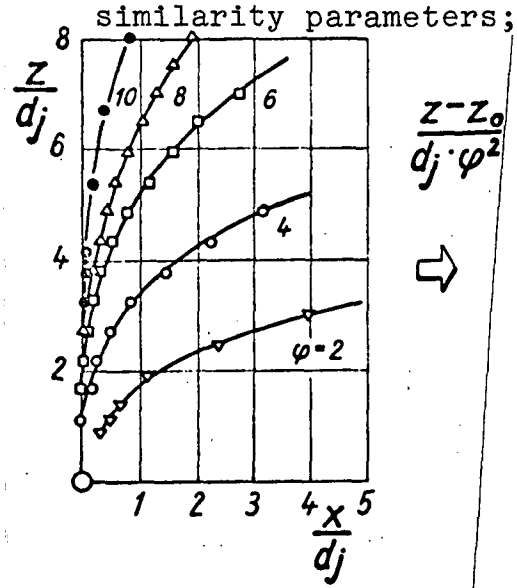
For the case of the plane incompressible jet (which is not relevant for our own investigations), it was Ehrich [47] who first treated the jet propagation using potential theory and conformal transformations. A common streamline or a vortex / 14
layer is assumed as the separation lines between the parallel flow, the jet and the "dead water" wake. A similar solution has been given by Ting/Ruger [48], where uniform pressure is assumed within the jet and parallel flow is assumed. It was possible for Ting, et al. [49] to extend this through small pressure differences by using the method of small disturbances in addition. A numerical solution has been given for the perpendicular jet ($\delta_j = 90°$). Girschowitsch [50], on the other hand, assumes that the jet is a pure boundary layer flow, which emerges from an infinitesimally thin slit. With certain simplifications

(for example, jet axis is a streamline of the basic flow, the mixing path lengths are constant along the jet axis) well known boundary layer relationships are used to determine the jet boundaries, the course of the axis and the center velocity.

The more important case of a round jet in a transverse flow was first theoretically discussed by Chang [51]. The problem consists of determining two essential flows for outside and inside of the separation surface. The solution for the region near the nozzle assumes equal pressures and contours along both sides of the surface. This assumption is no longer satisfied for distances farther away from the nozzle. Here the variable position of the vortices in space must be determined, which are arranged along the separation surface. The fact that the jet cross section is deformed in the shape of a horseshoe has been verified in experiments. (See Chapter 4.3.2).

The theoretical potential method of Fraser [52] is based on the idea that the jet propagation in the first approximation can be compared with the flow around a cylinder. This limits the usefulness of the analytical model to the region just behind the nozzle. Monical [53] replaces the jet by a vortex system which is arranged along a jet axis which has been determined empirically. The older Russian papers (mentioned in [57]) use purely kinematical solution methods for determining the jet axis, (geometric super-position of the velocity vectors). This then leads to a poor agreement with experiment, as expected. On the other hand, the more recent Russian papers introduce powerful methods based on aerodynamics. They are essentially based on the idea that the pressure forces and the centrifugal forces are in equilibrium. This has been developed by Ivanov [54] and Abramovich [24]. They differ primarily in the formation of the momentum equations, in the simplifying assumptions and in the solution methods when the jet axis coordinates are determined. /15

Jet for transverse flow $(\delta_j = 90°)$. Fluid dynamic similarity parameters; according to [702.



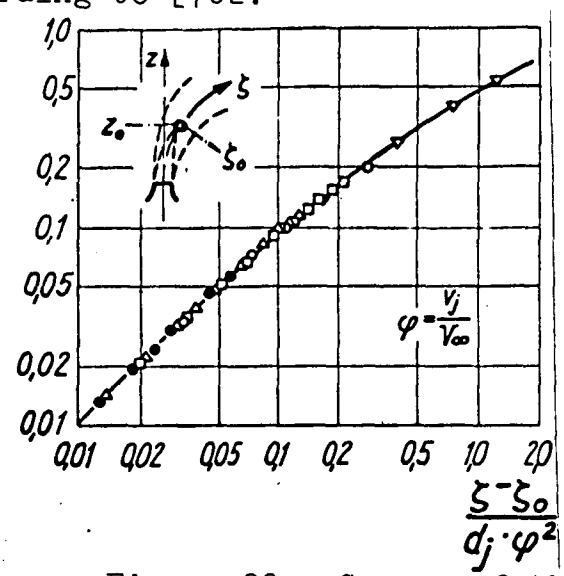
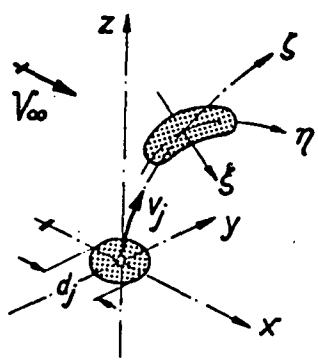


Figure 22. Course of the jet axis



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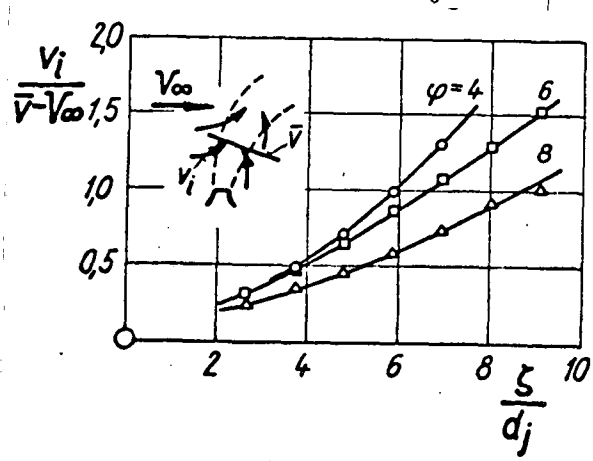

Figure 24. Relative inlet velocity at the jet edge.

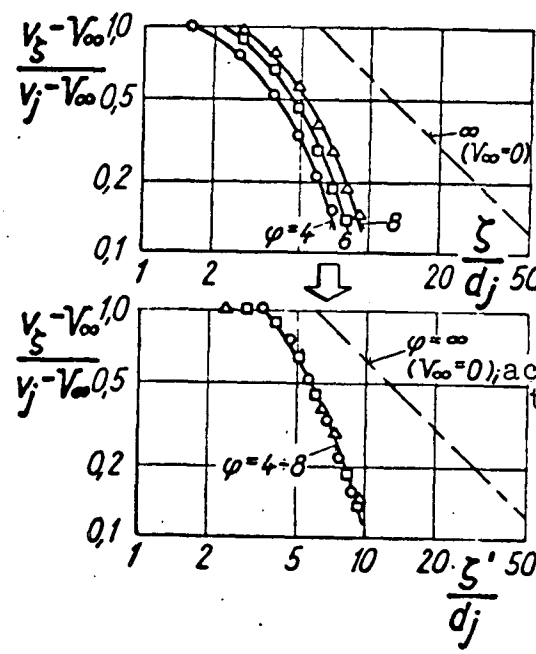

Figure 23. Course of the center velocity

Access variation of inclined engine jets in a parallel flow (Eq. see Appendix)

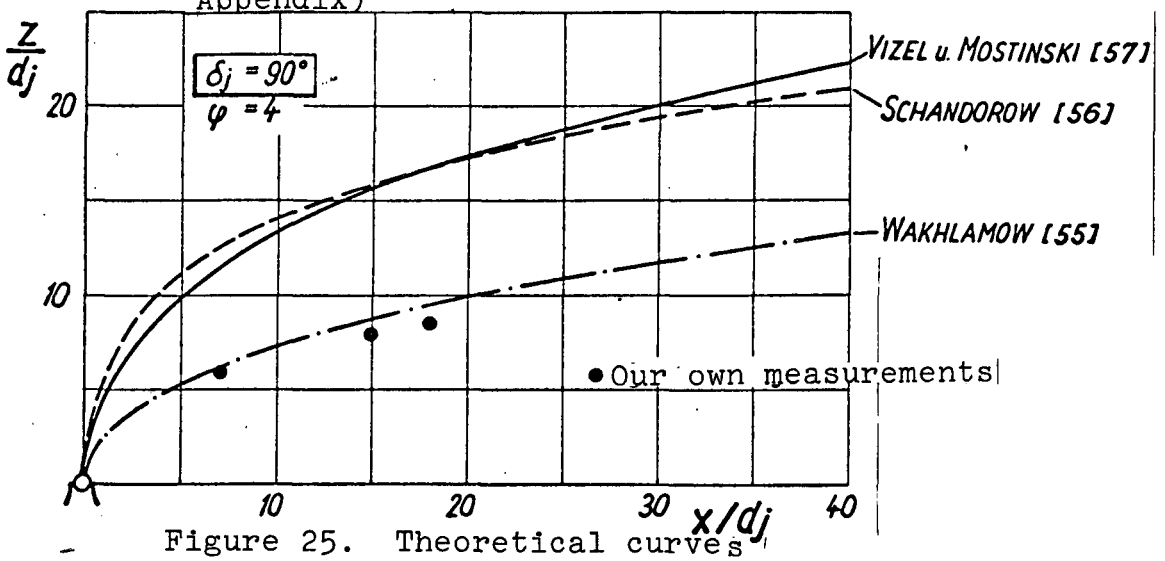

Figure 25. Theoretical curves

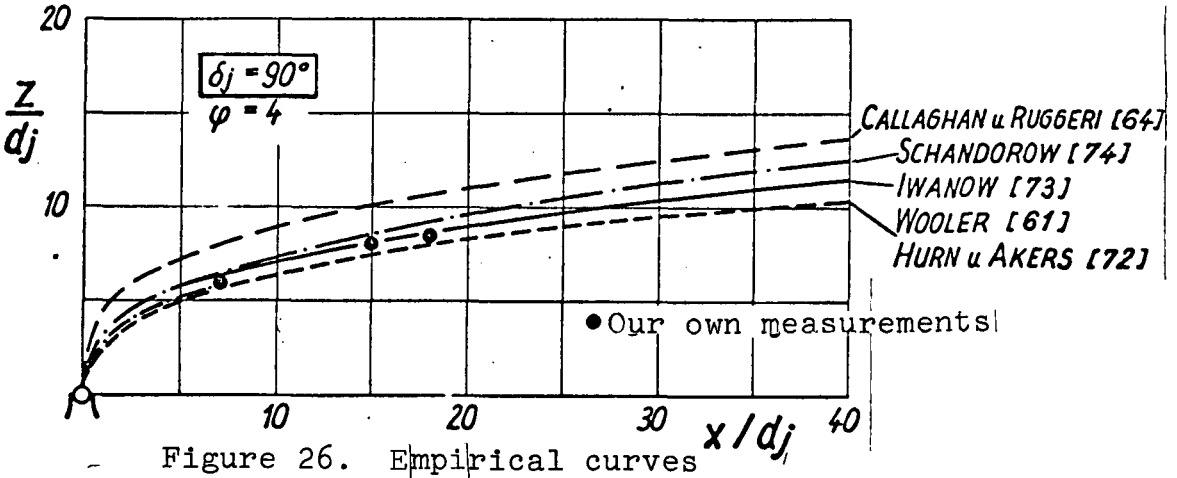

Figure 26. Empirical curves

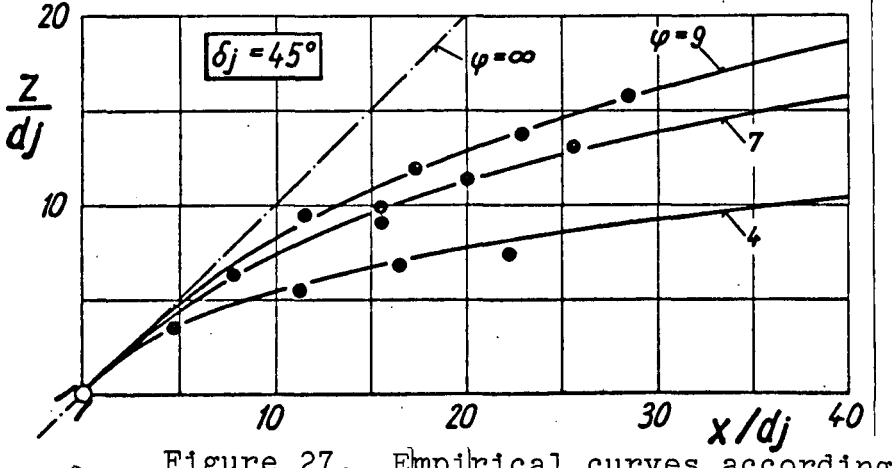

Figure 27. Empirical curves according to Ivanov [73]
In comparison with our own measurements (●).

Figure 25 shows some numerical examples, which have been calculated according to the formulas of Waklamov [55], Shandorv [56] and Vizel/Mostinski [57] (see Appendix, Table 2, Equations (1) to (3)). The methods, given in Chapter 24, [56] and [57] have a common weakness that the jet is assumed to be a drag body and that empirical force coefficients (c_{wx}, c_n) must be used in the coordinate expressions. The uncertainties regarding the magnitude of the coefficients and the range of validity of the equasions (velocity ratio, inclination angle) explain in part the considerable deviations in the curves. There is an additional contribution by Kirillov/Kudenko [58].

A study by Crowe/Riesebieter [59] is very empirical. It deals with the jet propagation as a function of the momentum ratio. Important influence variables obtained from smoke tunnel experiments are used to establish an equation for the coordinates of the jet axis.

Recently Wooler, et al. [60] have developed a theoretical model of the flow field, which is produced when a vertical (lifting) jet spreads out during transition flight. The improvement with respect to the papers mentioned above consists of the fact that the entrainment flow induced by the jet is also considered. Except for some assumptions on the geometry of the jet cross-section, this theory uses no empirical relationships for the jet axis. It is derived from the equations of motion. The velocity field induced by the jet is determined by replacing the jet by a sink-dipole distribution which characterizes the inflow effects or the spreading of the jet. This makes it possible to determine the induced downwind field over the wing, which is located just above the jet exhaust (in the near region). Wooler considers the new downwind distribution as an "effective curvature". He can then use one of the lifting surface theories to calculate the pressure distribution induced along the underside of

the wing. There is good agreement with experiments. Also, Wooler [61] developed a semi-empirical theory for calculating the pressure distribution along a flat plate in longitudinal flow, from which a vertical jet emerges.

By observing the jet in a transverse flow, it has been found that two strong an opposing vortices separate along its leeward side, and the intensity increases with the deflection. The assumption that this pair of vortices is primarily responsible for the induction effects, in the adjacent flow field, led Williams/Wood [62] to develop an elementary "vortex sheet" theory for calculating the induced velocity field. The assumption that the direction of the parallel flow is about the same as that of the jet in the vicinity of the jet boundary first restricts this solution to the far region of the jet (with a small inclination of the axis). Using the jet flap theory, it is also assumed that there is a constant momentum flux along the jet path, which means that the inflow is ignored. Empirical relationships are used to obtain the course of the jet axis. / 16

4.3.2 Experimental work

Even though several attempts have been made to describe the complicated flow fields by means of analytical models, the empirical partial solutions of this problem still represents the most reliable data. This is why they will be described in complete form. Lee [63] gave a short summary and selected a number of primarily experimental papers.

The first systematic investigations of a jet emerging perpendicularly into a parallel flow was performed by Callaghan/Ruggeri [64]. He derived an empirical formula for the jet axis coordinates (see Appendix, Equation 6). In other papers, Ruggeri investigates the influence of non-circular nozzle cross-sections

on the jet propagation [65] and determines the temperature profiles for a heated jet [66]. Gordier [67] carried out similar experiments in a water tunnel and derived formulas for the jet boundaries from colored thread photographs. He gives pressure and velocity distributions for the symmetry plane of the jet as well as for sections perpendicular to the jet axis. From this work it follows that the pressure field at the jet edge and therefore the inflow, depend greatly on the velocity ratio. The results, however, are restricted for the velocity ratios $\varphi \leq 6$ and for horizontal distances behind the nozzle of $x/d_j < 18$. Recently Mehmel [68] performed measurements of an air jet with a further variation of the parameters, (among others, jet inclination angle $\delta_j = 0°$ to $90°$). The velocity field of the jet and /17
in its vicinity (x,z) were measured both in magnitude and direction. Very detailed pressure distribution and direction measurements were carried out for Jordinson [69] in a perpendicular jet. There are numerous isovar figures given in this paper, which gives an exceptionally clear picture of the structure of the propagating jet. It is comparable with the structure of a flow around a porous cylinder having unequal suction.

The paper by Keffer/Baines [70] contains a detailed and fundamental physical and phenomenological description of a jet in a crosswind ($\delta_j = 90°$). A careful analysis of his own measurements was performed. By using a "natural" coordinate system oriented along the jet axis, appropriate fluid dynamic similarity parameters, are defined, which, for example, can be used to eliminate the influence of the velocity ratio or the momentum flux ratio. The left diagram in Figure 22 shows the course of the jet axes in x,z coordinates. There is a strong dependence on the velocity ratio φ. If the coordinate origin is not located at the center of the nozzle, but at the end point of the potential core ("the effective origin" of the completely turbulent jet: z_o, ζ_o), then all curves can be made to cover each

other for all values of φ (Figure 22 right diagram). The same universal representation can be made for the over-velocities along the jet axis, if the abscissa scale begins at the "apparent jet origin",(see Figure 23)*.Apparently, there are no similar correlations for plotting the peripheral inflow velocities (Figure 24). In general, Keffer/Baines assume that there are certain structural similarities for the jet cross sections in which the effect of the vortex pair is still small. Special measurements of the static pressure distributions have been made by Bradbury/Wood [71].

Finally, we will mention a few papers which are restricted to a formulation of an empirical equation for the jet axis. Hurn/Akers [72] and Wooler [61] only give relationships for the vertical jet. The equations given by Iwanow [73], Schandorov [74] and Rhezewski[75] only hold for different jet inclinations (see Appendix, Table 2, Equation(4) through (8)).The trajectory /18
curves calculated from this are shown in Figure 26. (Vertical jet $\delta_j = 90°$). This is shown in Figure 27 as well (inclined jet; $\delta_j = 45°$). Some random measurements of the author are also shown.

5. Wings for inhomogeneous incident flow

In Chapter 4.3.1, we pointed out analytical methods for determining the flow field of greatly inclined jets. They can only be used in exceptional cases, as a basis for calculating realistic and jet-induced lift distributions over wings (or lifting surfaces). The papers described here, on the other hand, refer to the representation of specific wing theories,

* Position: upstream from the nozzle mouth; definition: no mass flux, but finite momentum flux

in the case of inhomogeneous incident flow. However, a severe restriction has been made. We are only dealing with horizontal or very slightly inclined engine jets, if we are to derive practical calculation methods.

If we exclude the special case of a wall jet over a curved surface, then it seems appropriate to make a classification according to the use of the methods, (lifting line or lifting area methods). This classification approximately follows the chronological border as well.

5.1 Lifting line theories

All the computation methods based on this theory have the restriction that they can only be used for jets having a slight amount of over-velocity, because the Prandtl model of the lifting vortex line, strictly speaking, assumes a uniform flow. Koning [76] for the first time calculated the influence of a propellor jet on wings and lifting surfaces. Basic and additional flow were hard to find, and it is required that there is equal pressure on both sides of the jet boundary, and the kinematic flow conditions must be satisfied. The following restrictions must be made tor calculating the lift distribution: constant jet cross section along the wing chord, large ratio of the jet diameter to wing chord, homogeneous flow within the jet, friction and mixing processes are ignored. (The last assumption is also /19
the basis for all other methods mentioned in Chapter 5.1 and 5.2.) Lotz [77] gave a detailed criticism of this theory. Stüper [78] compared it with his own experimental results. (See Figure 28). v. Baranoff [79] gave an extension to a rotating jet having a small amount of inclination.

Bausch [80] also attempted to calculate the lifting line using the Prandtl integral equation. He replaced the (weakly)

inhomogeneous velocity distribution by a homogeneous velocity distribution of the basic flow and an "equivolent" geometric angle of attack distribution in the span direction. This is a "twisted replacement wing". A similar method has been developed by Vandrey [81], in which in addition the pressure condition is satisfied at the jet boundary. In this way, useful results are obtained not only for the total lift but also for the lift distribution along the span. A comparison with measurements by Schlichting/Jacobs [82] shown in Figure 29 demonstrates this.

Both methods consider the over-velocities in the span direction. Ruden [83], [84] investigated the case of incident flow over an infinite wing which is inhomogeneous (discontinuously) in the vertical direction using theoretical and experimental methods. Even though this is a plane problem, the influence coefficients of Ruden can also be used to estimate the lift changes produced by a round, off-center jet over a symmetric profile (random sample made by the author).Also we would like to mention a paper by v. Karman/Tsien [85].

5.2 Lifting surface theory

Wings with small aspect ratio and large lift coefficients, such as are encountered in modern aircraft, mean that the use of a lifting line theory is questionable. In addition, jet engines have small jet diameters compared with the wing chord. Graham, et al.[86] attempted to calculate the jet-induced lift changes, using the slender body theory for the case where the washed wing segment has an aspect ratio of $\Lambda = 1$. The restriction to small over-velocities was also dropped. Figure 28 shows that / 20
the experimental results of Stüper [78] lie between the valleys of both extreme theories. From this, Rethorst [87] concluded

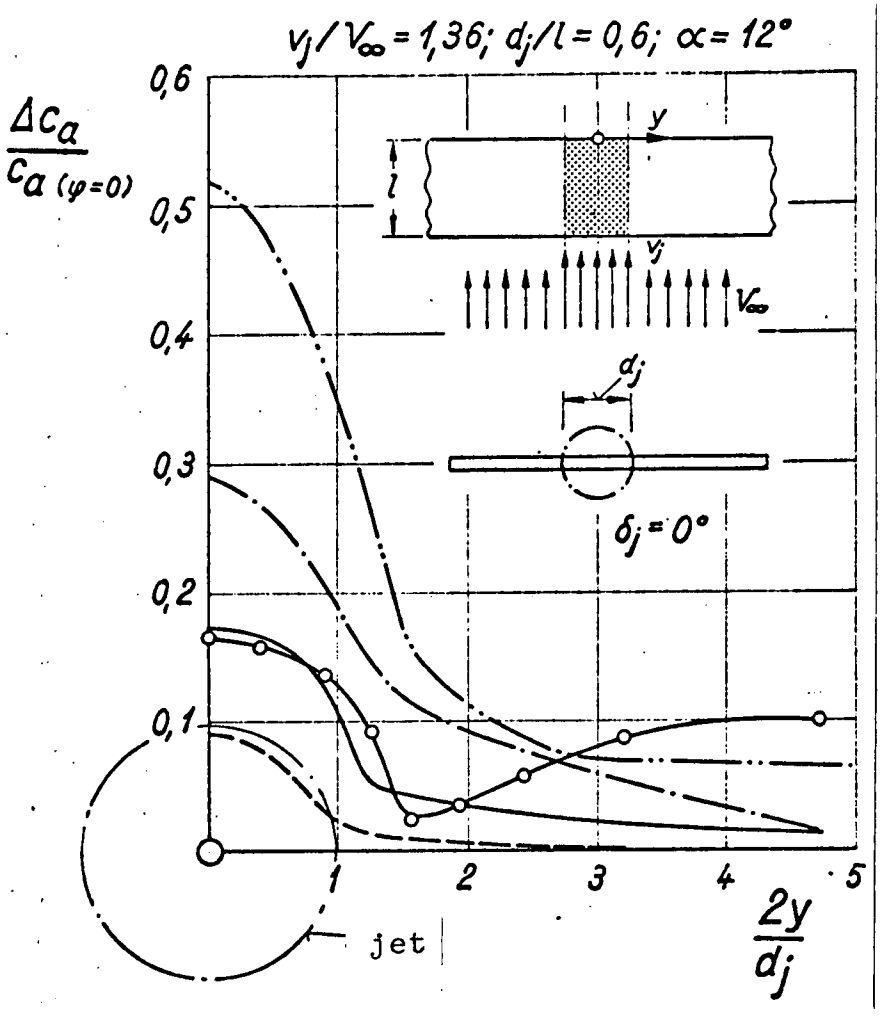

Figure 28. Inhomogeneous flow around a rectangular wing. Comparison of theory and measurement according to [87].

o	Measurement of Stuper [78]
—··—	Lifting lines, according to Koning [76]
—·—	Lifting lines, according to [76], extended calculation of Graham [86]
———	Lifting surface theory, according to Rethorst [88]
— — —	Slender body theory, according to Graham [86]

that a modified lifting surface theory, which would be half-way between the lifting line theory and the slender body theory, would describe the flow conditions in the best way. He then developed a method which assumes that there is a discontinuity surface between the jet and the outer flow. The new downwind distributions induced by this vortex layer are used to calculate the lift according to the lifting surface theory of Weissinger. Rethorst applied his method to over 400 different wing configurations in an extensive study [88]. He also determined optimum aspect ratios as a function of the jet diameter and as a function of the velocity ratio. Wu [89] refined and extended his theory to several engine jets. There are two additional papers, which are based on the Rethorst method which involve wings at large angles of attack. These are due to Cumberbath [90] and Wu [91]. Recently Weissinger [92] gave the solution of a plane flow problem, in which a wing is located in an exponential shear flow.

5.3 Wall jets over curved surfaces

The special case of a horizontal engine jet propagating along a lift-producing surface could be looked upon as a wall jet problem. The boundary layer character of the jet could be used in the interference analysis. This approach has been found to be fruitful in the treatment of the boundary layer and circulation effects involved during outflow from a wing. However, these are plane wall jets. The problem under discussion involves a round wall jet in an external flow. In addition, the curved surface does not follow immediately after the jet nozzle. We were not able to find examples of Coanda effects, formulated in this way in the literature. Only partial problems have been treated, for example, by Sforza/Herbst (three-dimensional wall jet in a medium at rest [93]), Bradshaw/Gee (plane wall jet with outer flow [94]) and Benner (plane wall jet in a medium at rest and a large distance between the nozzle and the surface [95]).

6. Experimental fundamental studies on jet interference at lifting surfaces. /21

In this chapter we will mention contributions which complement our own measurements.

6.1 Horizontal jet

The few papers on this special case were written before 1945, and have not been continued in a systematic way. Stüper [96], [97] first carried out force and pressure distribution measurements of a free jet passing through a wing for a medium at rest ($V_\infty = 0$). He also performed a preliminary study, the so-called "stand case", where the influence of various jet cross-sections and the influence of the jet eccentricity on the lift increase and the maximum lift were determined. In addition, theoretical attempts were made to determine the lift distribution.

Stüper [78] expanded the work to investigations in a basic flow, but he limited himself to small velocity ratios ($\varphi \leq 1{,}36$), and very small distances between the nozzle and the lifting surface ($x/d_j = 0.4$). Figure 30 shows the measured additional lift forces over the span for two angles of attack. (The pronounced valleys in the curves can be traced to wake effects of the nozzle). Falk [98] [99] carry out systematic forced measurements for a rectangular wing. In particular he investigated the influence of the distance to the nozzle. Figure 31 shows a typical result for slightly inclined jets($\delta_j = 0°$ to $6°$). It shows that the lift is sensitive to changes in the nozzle elevation. Falk also derived empirical coefficients for estimating the jet-induced lifts from the results (Figure 32). Küchemann and Weber wrote several reports on this topic [100], [101], [102]. The corresponding systematic pressure distribution measurements which would make it possible to analyze the overall interference effects

have not been published.* Raney/Kurn [103] gave one result for the fast flight phase (M_∞ = 0.74)(see Figure 33).

6.2 Vertical jet /22

Also, the important case of an inclined vertical jet has hardly been treated except for our own measurements [2]. The paper by Hammond/McLemore [104] gives some indications of how the lift can be influenced by changing the position of a vertical nozzle..

7. Summary

The present literature survey was produced within the framework of a research project on jet interference over lifting surfaces. It has the following purpose:

1) To give a summary on the state of research on this topic;
2) To demonstrate practical problems of jet interference for VTOL aircraft using typical examples;
3) To specify the requirement for basic experimental data, in order to formulate research problems;
4) To prepare trustworthy physical models;
5) To refer to work on the most important partial problems;
6) To demonstrate the difficulties of the theoretical approach;
7) To point to comparable and additional contributions, in addition to our own contributions;
8) To find suitable methods for analyzing our own experimental results;
9) To prepare a bibliography of the most important papers.

We would like to mention the following topic groups:

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* Our own measurements are being evaluated.

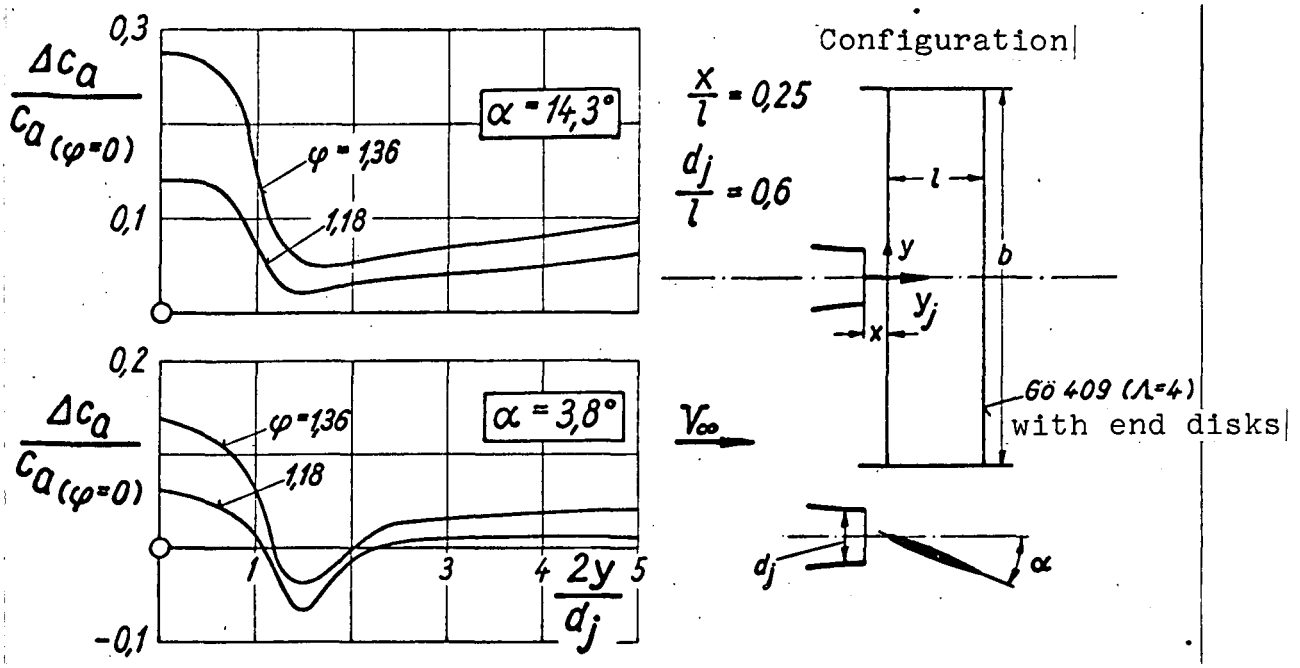


Figure 30. Measurements of Stuper [78]

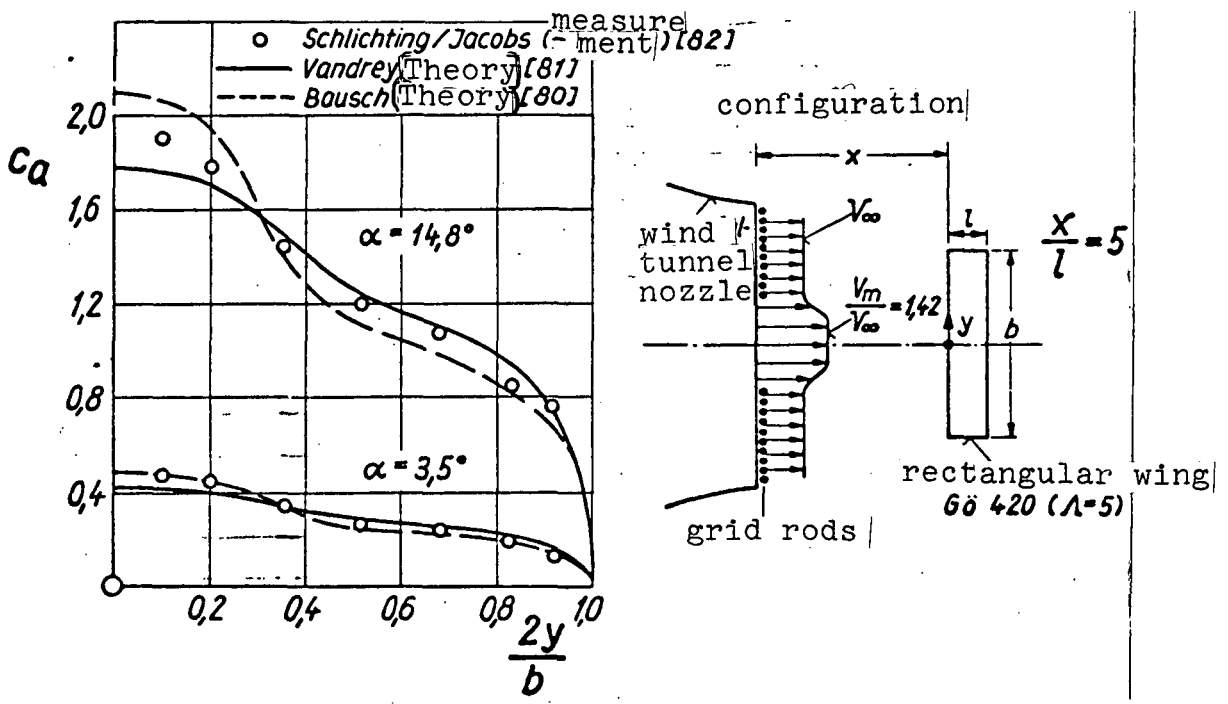


Figure 29. Comparison of measurement and theory according to [82].

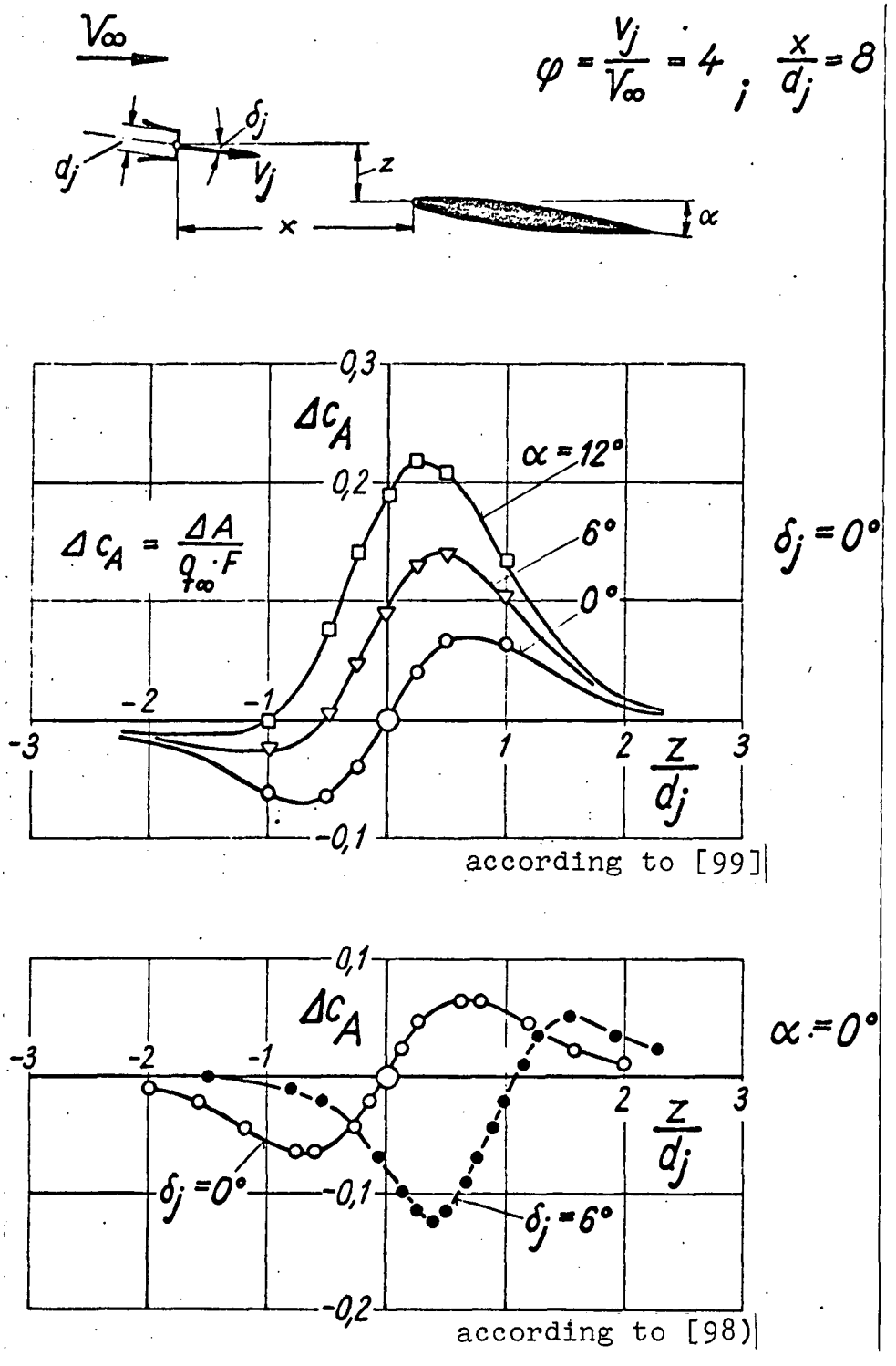


Figure 31. Lift changes of a lifting surface induced by an engine jet.

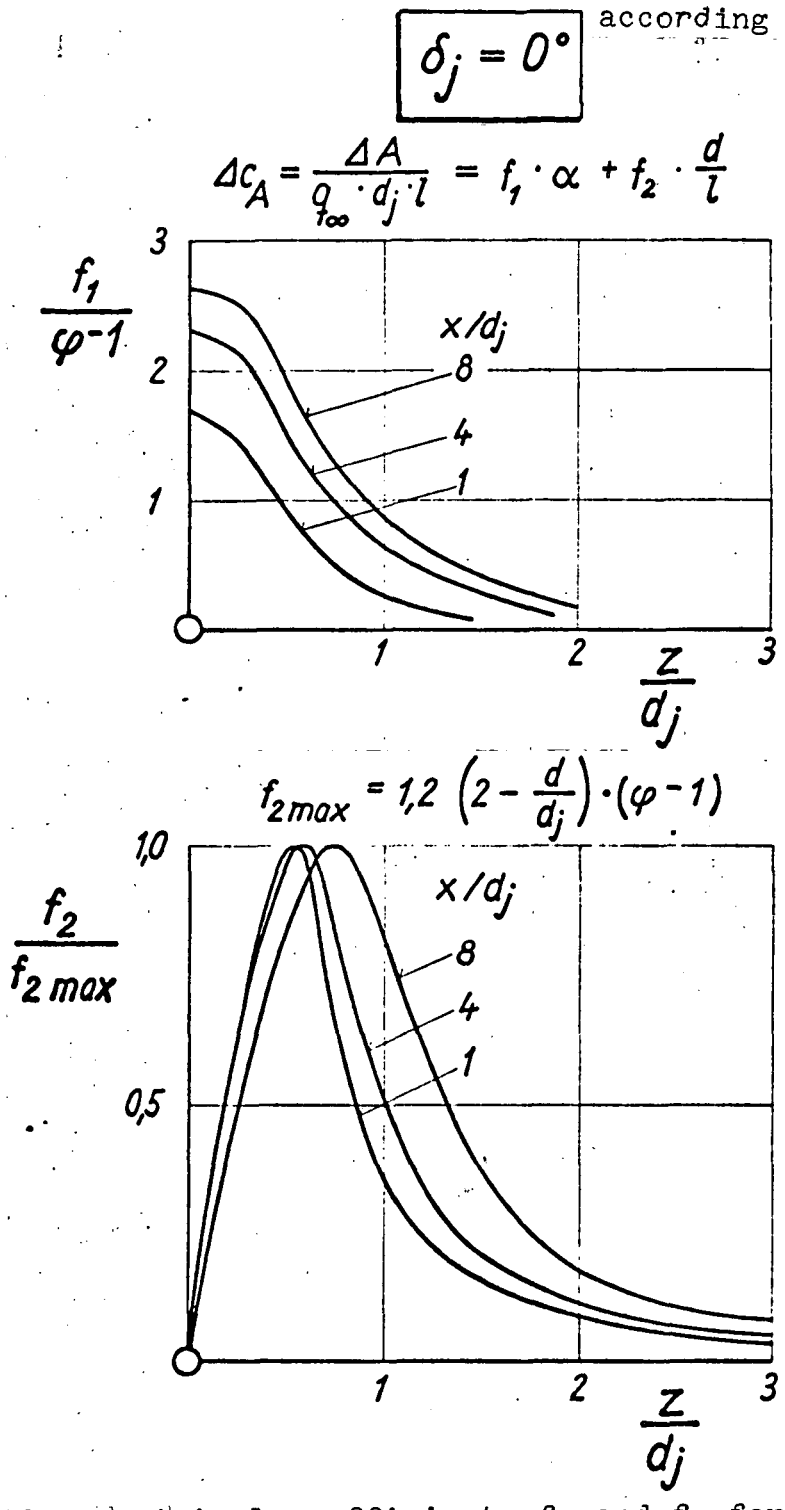


Figure 32. Empirical coefficients f_1 and f_2 for determining the jet-induced lift.

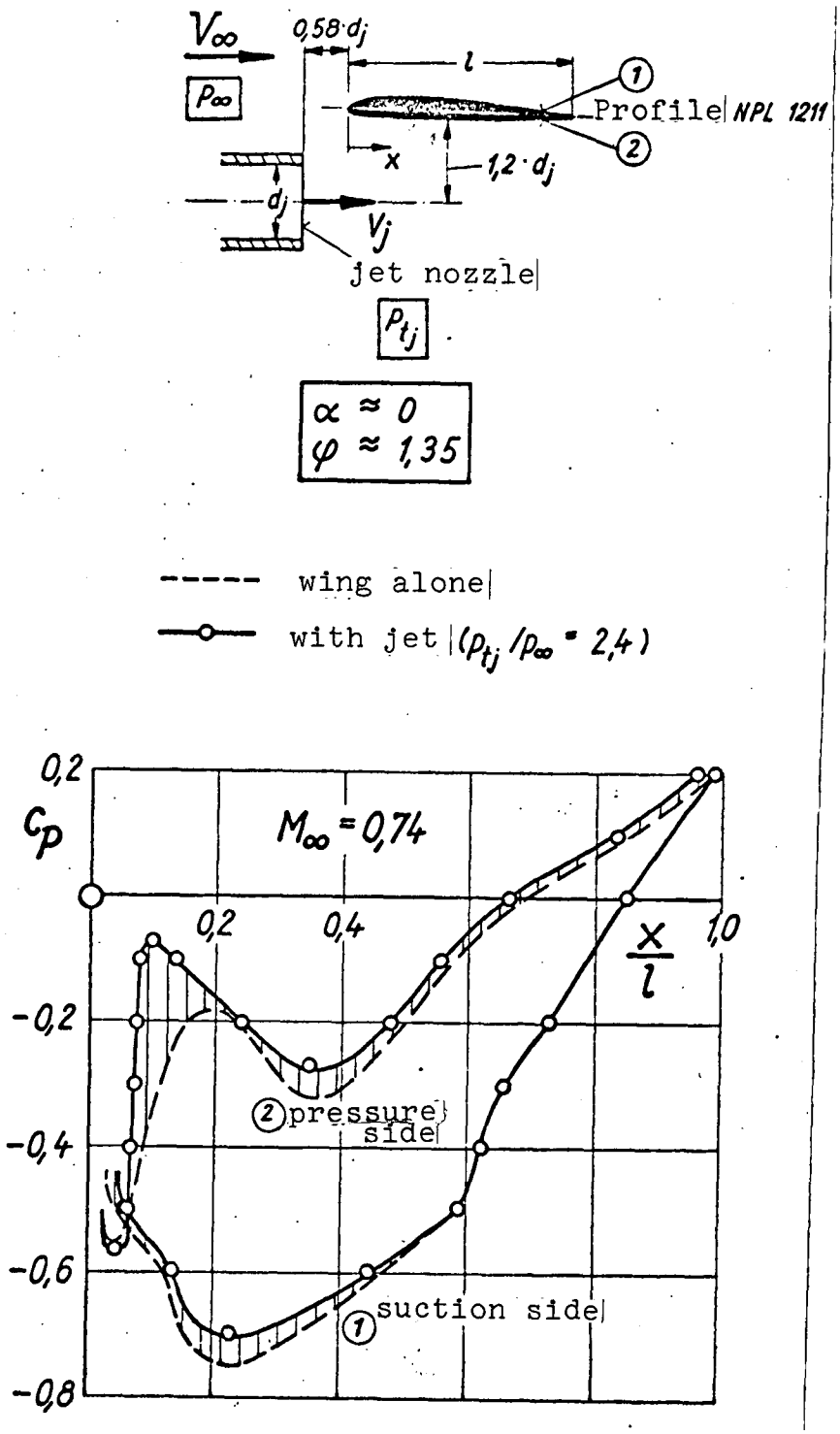


Figure 33. Pressure distribution of a NPL-profile with and without engine jet; according to [103].

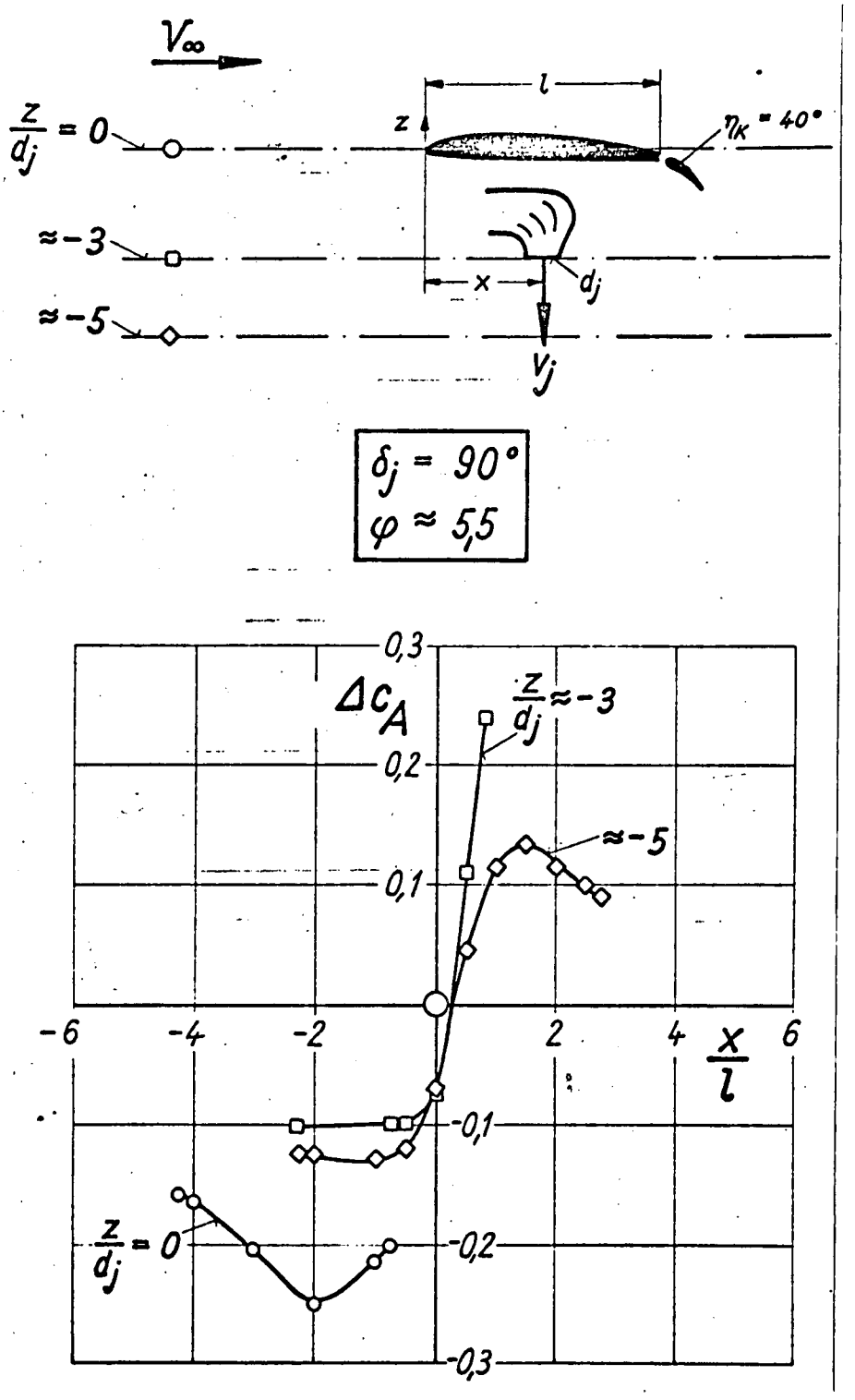
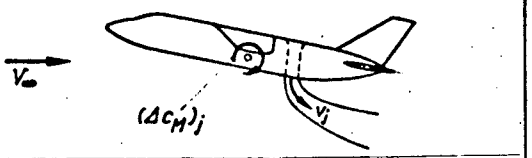
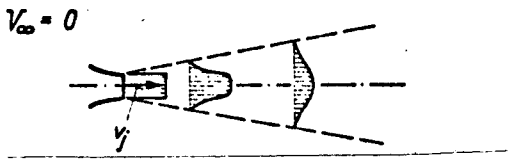
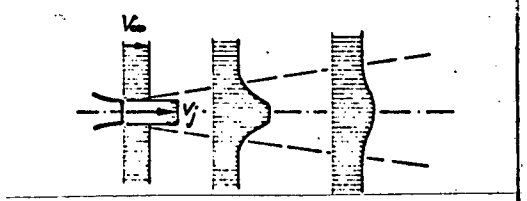
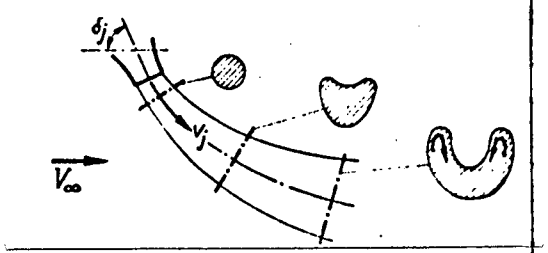
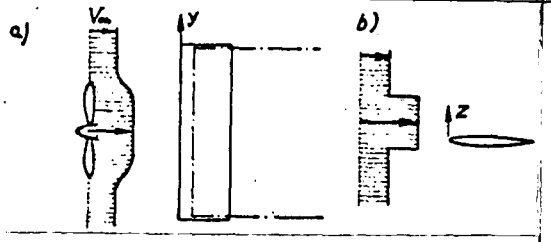
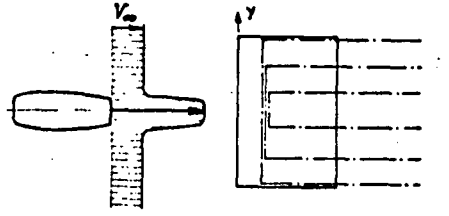
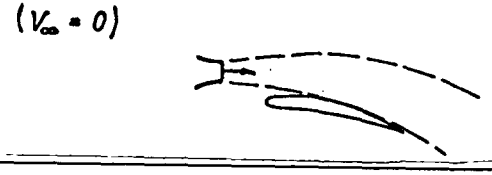
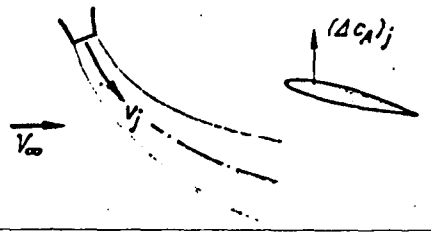


Figure 34. Jet induced lift for various positions of a vertical jet; according to [104].

TOPIC STRUCTURE OF LITERATURE SURVEY - TABLE 1

Chapter	Topic		Jet Incl.	Problem	Ref.
3.	Interference observations of special VTOL-projects (Figs. 1-16)		δ_j = 0°-90°	Influence of the engine jets on longitudinal stability	[1], [3] to [15]
4. 4.1	Propagation of free jets Jet in surrounding air at rest (Fig. 17)		-	Fundamentals of jet propagation	[16] to [36]
4.2	Jet in basic flow with the same direction		0°	Mixing of free jet and parallel flow; velocity distribution; isoclines outside of the jet edge.	[14], [15], [37] to [45]
4.3	Jet with inclination with respect to basic flow (Figs. 22-27)		0°-90°	Course of jet axis; deformation of the jet cross section; resulting flow field.	[24].[46] to [62] (theor.); [63] to [75] (empirical)

TOPIC STRUCTURE OF LITERATURE SURVEY - TABLE 1

Chapter	Topic		Jet Incl.	Problem	Ref.
5.	Wing for inhomogeneous incident flow. Lifting line theory. (Fig. 29)		0°	Calculation of the jet-induced lift for weak inhomogenuities of the basic flow. +a) horizontal b) vertical	[76] to [85]
5.2	Lifting area theory (Fig. 28)		0°	Calculation of the induced lift for large over-velocities of the jet.	[86] to [92]
5.3	Wall jets (Coanda effect)		0°	Three-dimensional wall jet for large distance between nozzle and profile	[93] to [952
6.	Experimental fundamental study of jet interference (Figs. 30 - 34).		0°-90°	Determination of the jet-induced lift of the elevator; pressure distribution along the profile; flow field in the vicinity of the profile.	[2],[96] to [104].

1) Fundamental studies on jet interference for an isolated lift-producing body at a large distance from the nozzle;
2) Phenomenological and quantitative interference examples for specific VTOL projects;
3) Theoretical and experimental contributions of the propagation of an inclined jet in a parallel flow;
4) Lifting surface theories for inhomogeneous incident flow;

The conclusions obtained as a result of a review of the literature can be summarized as follows: /23

1) Fundamental studies have almost exclusively been performed for the special case of a horizontal jet.
2) There are no pressure distribution measurements over lifting surfaces needed to interpret the interference effects.
3) The partly considerable changes in the longitudinal stability induced by engine jets require a careful optimization of the relative position of the nozzle and the lifting surfaces.
4) The physical models of propagation of inclined jets are not yet fully developed. Therefore, most of the calculation methods are of an empirical nature.
5) Lifting surface theories for inhomogeneous incident flow require very restrictive simplifying assumptions, in particular it is necessary to restrict oneself to almost parallel jets. It is quite difficult to extend the theory to inclined jets.
6) Systematic experiments are necessary in order to obtain useful data for project planning.

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