ICAS Paper No. 68-11

SOME RESULTS OF AERODYNAMIC RESEARCH AND FLIGHT INVESTIGATION OF THE EFFECTS OF BOUNDARY LAYER CONTROL BY BLOWING

by

Zbyněk Jaňour and Vilém Kočka
Aeronautical Research and Test Institute
Prague, Czechoslovakia

The Sixth Congress of the International Council of the Aeronautical Sciences

DEUTSCHES MUSEUM, MÜNCHEN, GERMANY/SEPTEMBER 9-13, 1968

Preis: DM 2.00

SOME RESULTS OF AERODYNAMIC RESEARCH AND FLIGHT INVESTIGATION OF THE EFFECTS OF BOUNDARY LAYER CONTROL BY BLOWING

Z. Jaňour and V. Kočka
Aeronautical Research and Test Institute /ARTI/
Prague - Letňany, Czechoslovakia

Abstract.

Following problems were investigated by wind-tunnel measurements: Blown flaps having various forms, especially a slotted flap with blowing from its leading edge. Simultaneous blowing over flaps, ailerons and from the wing nose, especially near the maximum lift. Slip stream deflection by blowing over horizontal rudder, etc. The results were applied in designing an experimental aeroplane.

In flight tests the influence of blowing on aerodynamic and flight characteristics of the aeroplane was investigated, mainly the restitution value of the blowing coefficient, stalling characteristics and controlability after interruption of blowing.

Special methods were developed for tunnel and flight testing.

Introduction.

The research work on some problems of BLC by blowing and on the jet-flap scheme was conducted at ARTI during several years with the aim to investigate the possibilities of its application to STOL aeroplanes and to become acquainted with special problems occuring by their testing and designing. Besides some problems of general, basic character, the research was focussed upon the development of an experimental aircraft with BLC. To this purpose a conventional small two-engine aeroplane /type Morava L-200/ was adapted. The investigations were therefore limited to classical forms of wings and flaps.

The results of wind-tunnel investigations, of flight tests as well as some theoretical solutions are contained in many internal reports of ARTI; the main results of the aerodynamic research are summarized in a Summary Report (1). In the present paper some special problems will be emphasised.

I. Some results of wind-tunnel research.

/by Z. Jaňour/

1. The influence of the shape of the blown flap on the jet flap efficiency.

A symmetrical wing between end-plates was tested with three interchangeable flaps of various forms /see fig. 1/

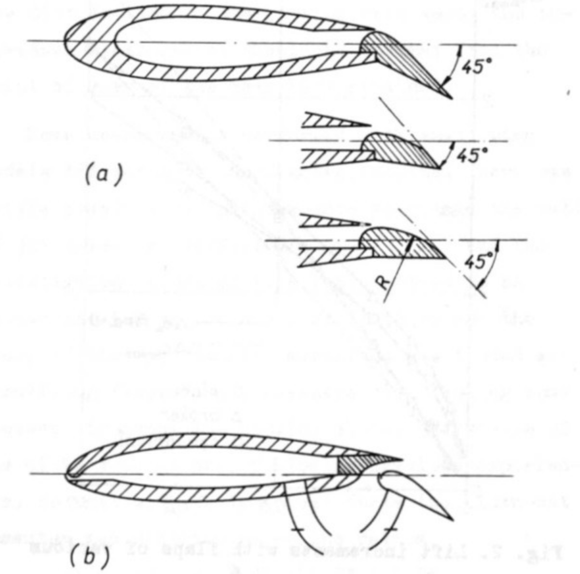


Fig. 1. Wing model sections. Size 0,2mx0,2 x).
Basic profile: a/ NACA 0018, 20% flap.
b/ NACA 63A416, 25% flap.

a/ flap with flat upper surface following a circular rounded nose.

b/ flap the top surface of which was broken three times by angles of 15°.

c/ flap having circulary cylindrical upper surface.

The angle formed by the tangent to the upper surface at the trailing edge and by the basic wing chord was the same for all three flaps, namely 45°.

---

x) Note: Instead of decimal points commas are used.

The upper surface was blown by a jet issuing from a slit in the rear edge of the basic part of the wing.

It is natural that - without blowing over the flap top surface - the largest lift values are attained with the first /flat/ flap, becouse the primary effect for lift increase by a flap is the amount of lowering the trailing edge. On the other side the deflection of the jet effected by the flap is due to the Coanda effect which can be influenced by the longitudinal curvature of the deflecting surface. In order to investigate this we need to compare the lift increments due to blowing. This is done in fig. 2 which shows the lift increments at a fixed /zero/ angle of attack as well as the maximum lift increments for the given wing fitted with either of the three flaps.

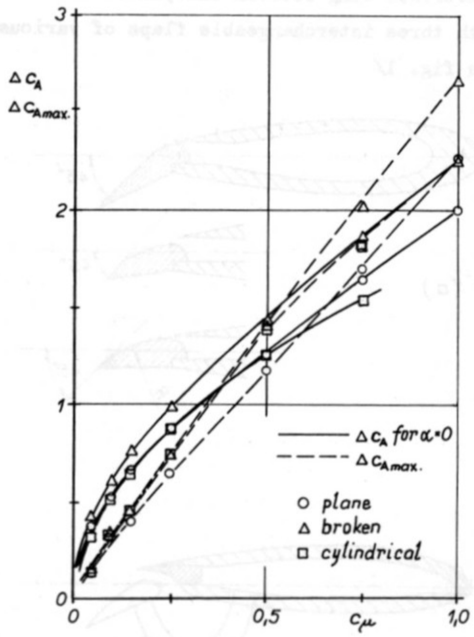


Fig. 2. Lift increments with flaps of various forms. Re $\sim$ 0,25x10^6.

The best lift increments are reached with the broken flap surface. The lowest increments with the cylindrical surface are due to premature separation of the jet from the surface before reaching the trailing edge. This can be observed also by calculating the directions of the reaction force from the ratio of the longitudinal force /negative drag/ to the lift, so as measured in free air. The deflection angles were

for flap 1 /flat/	48,5°
for flap 2 /broken/	47,0°
for flap 3 /cylindrical/	42,5°

Higher amounts of deflection with the flaps 1 and 2 may be explained either by an aerodynamic force induced by the mixing of the jet with the ambient air, or as a real deflection caused by asymmetrical mixing on both sides of the jet.

A slotted flap with blowing over its upper surface from a slot in the flap leading edge, as illustrated in bottom of fig. 1, was envisaged for application on the experimental aircraft in order to maintain good lift characteristics in take-off or landing also without using blowing. With blowing the slotted flap proved to give slightly higher lift values than a corresponding plain flap.

It is a disadvantage of the slotted flap with blowing from its nose that the optimal positions for maximum lift relatively to the basic part of the wing are strongly dependent not only on the flap deflection, but also on the value of the jet momentum coefficient. To determine the optimal positions large systematic sets of measurements are to be undertaken. An example is shown in fig. 3.

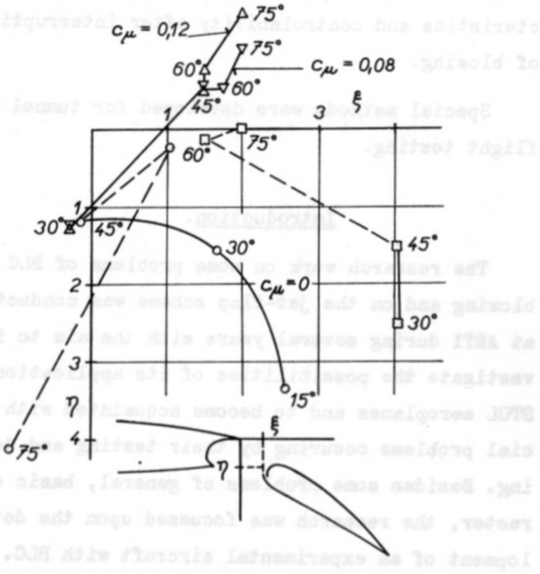


Fig. 3. Optimal positions of a slotted flap. Basic profile NACA 63A415, 25% flap. Re$\sim$1,3x10^6.

The coordinates ξ, η give the position of the lip of the blowing slot in the flap nose relatively to the rear edge of the basic part of the wing.

The changes of the optimal positions with blowing rate are largest during the restitution of potential flow over the flap. The movements of the optimal position with the flap deflection seem often not to be smooth. I must be stated that, in many instances, there could be found more lift maxima in different positions, some of them falling out of the investigated region.

The measurements on aerofoils with blown flaps verified the approximate relations for the lift increments by blowing at $\alpha = 0^{\circ}$, i.e.

$\Delta c_A \sim c_{\mu}$ for $c_{\mu} < c_{\mu r}$ /under-restitution range/

$\Delta c_A \sim \sqrt{c_{\mu}}$ for $c_{\mu} > c_{\mu r}$ /over-restitution range/

For maximum-lift increments the relation

$$\Delta c_{A\,max} \sim c_{\mu}^{0,82}$$

was found in most cases.

2. Blowing from the leading edge of the wing.

It is well known that with increasing rate of blowing the stalling angle of jet-flapped wings diminished down to the values approaching $\alpha \sim 0^{\circ}$. To remedy this it is intended to prevent the premature separation of the flow on the wing leading edge by blowing along the upper side of the wing from a slot in the leading edge. Of course, the slot should be placed upstream of the presupposed position of the point of separation.

The effect of blowing out of the wing nose slot only was first investigated. With growing rate of blowing the effect consists in restituting the potential flow over the wing upper side and finally over the deflected flap, thus delaying abrupt separation to higher incidences. Within the restitution range of the jet momentum coefficient the lift at moderate angles of attack is little influenced. An overall lift increase occurs, of course, with higher blowing rates, caused by the jet-flap effect of the jet passing over the trailing edge with over-abundant momentum. These effects are illustated in fig. 4 gained from measurements on a small wing profile model.

Generally blowing over flaps is more efficient mean for increasing lift than blowing from the leading edge at the same rate.

3. Combined blowing.

With blowing simultaneously from several slots, e.g. on wing leading edge and over flaps /and over ailerons, may be /the overall jet momentum coefficient

$$c_{\mu} = c_{\mu N} + c_{\mu K} + c_{\mu Q}$$

must be taken in consideration as a measure of power required for blowing. /The coefficients $c_{\mu} = m_{\mu} V_{\mu} / (qF)$ are related to the total wing area F./ The efficiency of combined blowing depends primarily on the distribution of the blowing rate among the individual slots, which should be optimal from the point of view of the best lift attained.

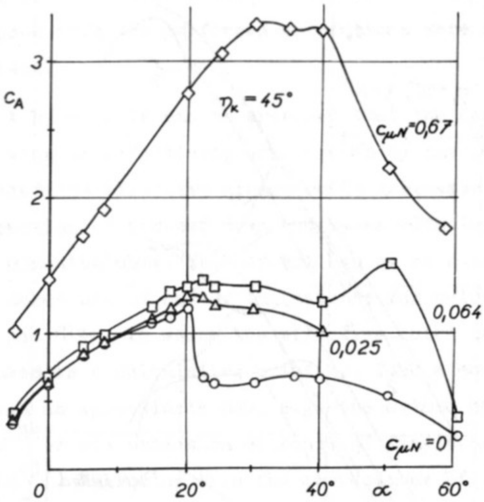


Fig. 4. Effect of blowing from the wing leading edge. Basic profile NACA 63A416, 20% plain flap. Re = $0,25 \times 10^{6}$.

Some measurements performed with small wing models did not give encouraging results. There was little possibility in the models to change the ratio of jet momentum coefficients $c_{\mu N} / c_{\mu K}$, and the investigated values of this ratio proved to be either too low or too high. For this reason the model of the experimental aeroplane was fitted with throttling flaps in all channels distributing compressed air among the blowing slots. The widths of the slots were chosen, following previous experiences, so that with fully opened ducts the blown-out momentum was distributed by the ratios

$$c_{\mu K} : c_{\mu Q} : c_{\mu N} = 0,40 : 0,24 : 0,36 .$$

Expressed as the ratio of momenta blown out at the leading edge and at the rear of the wing, i.e.

$$c_{\mu N} / (c_{\mu K} + c_{\mu Q}) = 0,55.$$

/In this ratio the sum $c_{\mu K} + c_{\mu Q}$ is somewhat confusing, because the flaps and the ailerons have different angles of deflection./

The resulting lift curves without blowing and with blowing at two distinct values of the total momentum coefficient are shown in fig. 5. For each curve the respective throttling of the air inlet is informatively indicated.

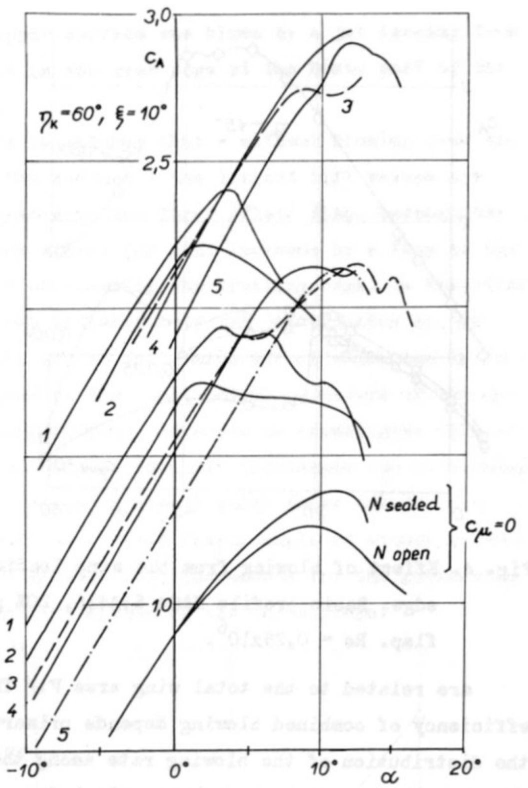


Fig.5. Effect of blowing ratio $c_{\mu N}/(c_{\mu K} + c_{\mu a})$. The E-33 aeroplane model without horizontal tail, without propellers. Blowing:

	flaps	ailerons	wing nose
1	full	full	0
2	full	full	1/3
3	full	full	2/3
4	full	full	full
5	2/3	2/3	full

The deciding datum is the value of maximum lift coefficient, which is shown to be the greatest with full admission of the blown air into all slots, or with some throttling of the air admission to flaps and ailerons. The distibution given by the above ratios proved thus to be approximately optimal.

Two important features must be mentioned. Firstly, the blowing slot in the wing leading edge must be placed forward enough, in order to prevent separation also at large incidences; in the profile of the measured wing it was placed in 0,2 per cent of the chord. Secondly, the application of blowing out of the slot in the wing nose is most important between the fuselage and the nacelles with the aircraft type in consideration, so as confirmed by measurements.

The blowing slot in the leading edge represents a serious perturbation on the wing surface when there is no blowing. In the bottom of the fig. 5 two lift curves are compared, one relating to the aircraft model with opened slot, the other to the same model with the slot sealed by a masking tape. The difference in maximum lift values is considerable.

Another confirmation of the advantages of the concept of combined blowing is given in fig. 6.

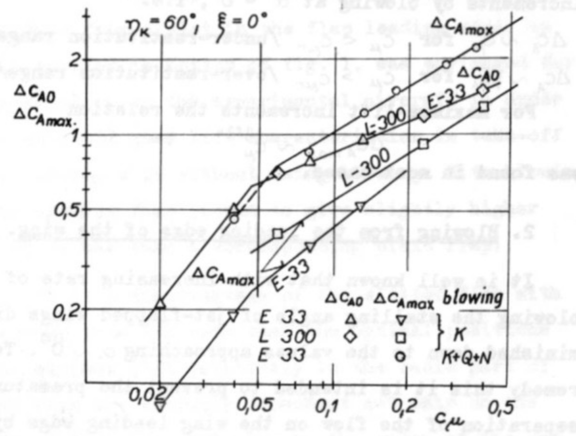


Fig. 6. Lift increments and maximum lift increments by blowing over flaps and ailerons and by combined blowing. Aeroplane models with horizontal tail.

Here the lift increments by blowing on the experimental aircraft model /E-33/ are compared with lift increments on a very similar model /L-300/, which differed from the former mainly by the type of flaps. Whereas the E-33 model had 25 per cent slotted flaps with blowing out of the flap nose, the L-300 model was fitted with plain flaps blown from the rear edge of the basic part of the wing. Also, in the L-300 blowing from the wing leading edge was not provided. The lift increments at zero angle of attack Δc_{A0} were the same for both models. With blowing over flaps only, the maximum lift increments $\Delta c_{A max}$ on E-33 model were lower; this was caused by the perturbation formed by the open slot on the wing leading edge on one hand, and, on the other hand, because the slotted flaps were not, incidentally, placed in correct optimal positions. Despite of the last fact, the maximum lift increments with combined blowing proved to be far better.

4. Induced drag of wings with blown flaps between end-plates.

A relevant problem arises when we attempt to reduce the measured values of the drag coefficient to an infinite aspect ratio with jet-flapped wings, especially with wings between end-plates. Here, the

value of the effective aspect ratio must be determined. When the geometrical aspect ratio is low and does not allow for usual methods of calculating the effective aspect ratio /taking the effect of end-plates into account/, this value is usually determined by measuring the lift curve slope of the wings.

In such a way, for a large wing model /0,6m x 1,2m/ between large end-plates an effective aspect ratio 11,6 was found. The wing was fitted with a slotted flap with blowing slot in the flap nose. In fig. 7 the results of measurements of the longitudinal force, i.e. the difference between the horizontal component of the reactive force and the wing resistance, are plotted as function of the jet momentum coefficient. The results were corrected from AR = 11,6 to infinite aspect ratio, thus they should not contain any induced drag. When the horizontal component of the jet reaction force was subtracted, the profile drag remained, as indicated by dashed lines.

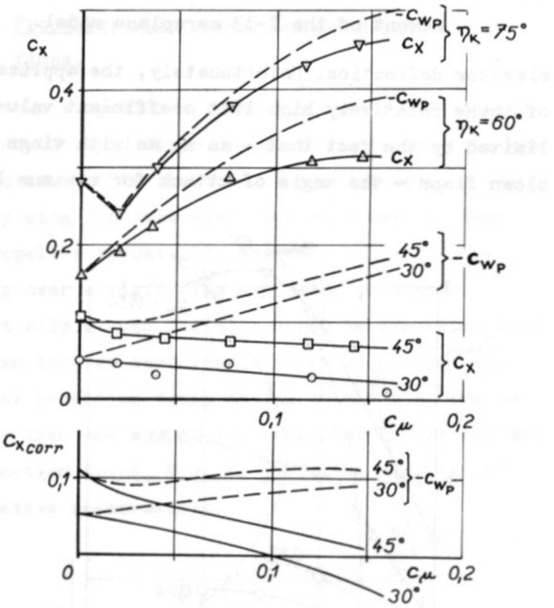


Fig. 7. Longitudinal force on a wing with blown slotted flap between end-plates. $\alpha = 0^\circ$, Re = $1{,}3 \times 10^6$.

In this case the profile drag can be considered as almost wholly of frictional origin, because, in the over-restitution region of blowing and at zero incidence no separated regions of flow over the wing can be expected. It is thus surprising that the profile drag should increase strongly with increasing jet momentum, as can be seen in the upper part of fig. 7. It seems to be more plausible to suppose that the performed corrections were insufficient.

A hypothesis can be proposed that the chord of the wing is effectively prolongated by the jet flap, so that the effective aspect ratio decreases and the proportion of induced drag increases with increasing jet momentum rate. This effect can be calculated if one makes use of one of the methods for calculating the jet flap, in which the effective chord length is used as a calculating quantity. Such a method is, though an approximate one, e.g. the method by Stratford$^{(2)}$ or its extension to wings of finite aspect ratio$^{(3)}$. Following this the corrections of the longitudinal force and the profile drag were informatively recalculated at lower values of flap deflection /30°, 45°/ with the result plotted in the lower part of fig. 7. The slight increase of the profile drag is much more acceptable than the previous results. The effective chord was prolonged, within the range of measured values /$c_\mu \leq 0{,}15$/, by as much as 15 per cent and the effective aspect ratio decreased down to approximately 8. For large flap deflections recalculations were not performed, because the theory is linearized and thus limited to small angles. - By this example the above hypothesis becomes very plausible.

5. Pitching moment of the aeroplane with blown flaps.

It is well known that the jet flap causes strong nosedown pitching moments acting on the wing. The growth of the pitching moment is shown in fig. 8 for

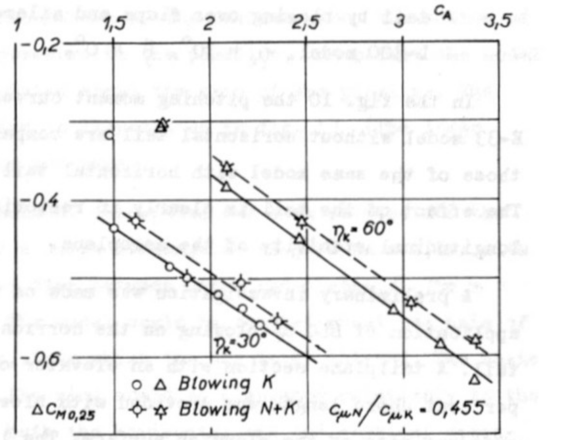


Fig. 8. Pitching moment vs. lift dependence of an aerofoil with blowing. NACA 63A415 section, 25% slotted flap, $\alpha = 0^\circ$.

a wing with 25 per cent slotted flap with blowing out of the flap nose. It can be also observed that additional blowing from the wing leading edge reduces the pitching moment only a little, as shown by dashed lines in the figure.

With the complete aeroplane this unfavourable effect is partly automatically compensated. By blowing over deflected flaps the downwash angle downstream of the wing is increased so that the incidence of the horizontal tail surfaces decreases. This effect furnishes a positive contribution to the pitching moment of the aircraft and compensates - at least partially - the negative moment due to blowing. The change of the incidence on horizontal tail is shown in fig. 9, so as it has been measured on the L-300 model.

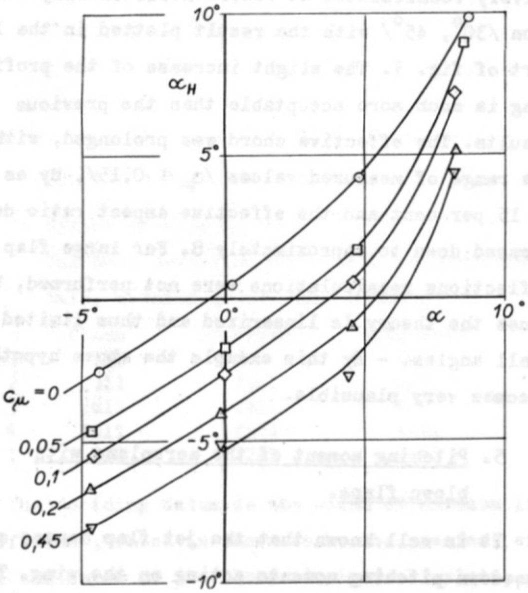


Fig. 9. Change of angle of attack on horizontal tail by blowing over flaps and ailerons. L-300 model, $\eta_K = 30^\circ$, $\xi = 0^\circ$.

In the fig. 10 the pitching moment curves of the E-33 model without horizontal tail are compared with those of the same model with horizontal tail added. The effect of the tail is clearly in restoring longitudinal stability of the aeroplane.

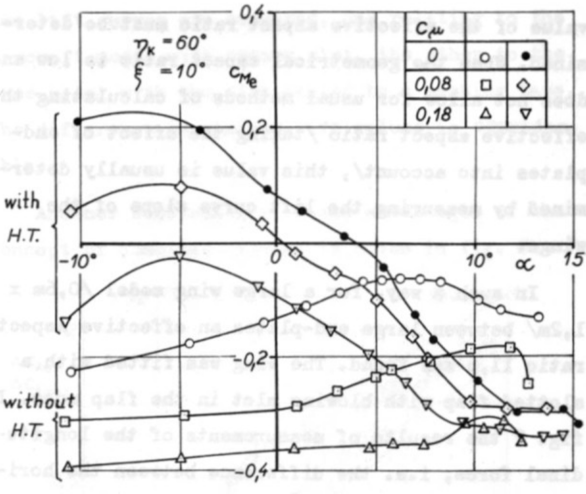


Fig. 10. Effect of horizontal tail on the pitching moment of the E-33 aeroplane model.

A preliminary investigation was made on the application of BLC by blowing on the horizontal tail. A tailplane section with an elevator of 45 per cent chord length was provided with blowing over one side of the elevator surface. The lift was considerably increased by blowing. The maximum lift values attained at different intensities of blowing are plotted in fig. 11 as function of the elevator deflection. Unfortunately, the applicability of these relatively high lift coefficient values is limited by the fact that - as so as with wings with blown flaps - the angle of attack for maximum lift strongly diminishes with increasing blowing intensity. So, at moderate angles of attack of the aeroplane the horizontal tail with blown elevator could become stalled. In the figure, by dashed lines are indicated the approximate limits on which the maximum lift is attained at the indicated angle of incidence of the horizontal tail surface. The region of

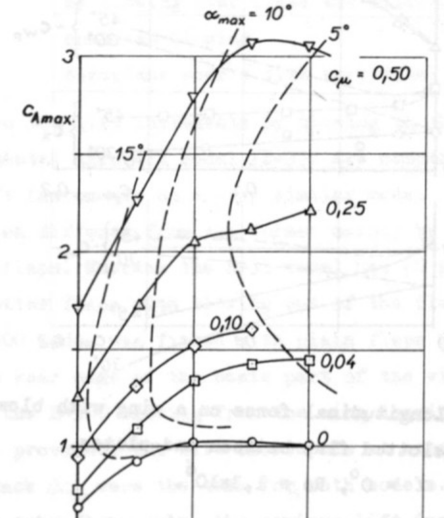


Fig. 11. Maximum lift of a tail-unit section. NACA 0010 section, 45% rudder. Re = 0,25 x 10^6.

applicable values of elevator deflection and of $c_{A\,max}$ coefficient is situated to the left of these limits.

The full applicability of BLC on the horizontal tail could be restored by addition of blowing out of a slot in the leading edge of the tailplane. But in this case there would be unavoidable to provide the reversibility of blowing with the sense of rudder deflection, i.e. blowing either over the upper surface or over the lower surface of the tailplane.

During flight tests with the experimental aircraft, BLC on the tailplane was in no case necessary.

6. Propeller slip stream deflection by blown flaps.

If the propeller slip stream has to be deflected by means of rigid flaps, large flaps or flap systems are necessary. The resultant force acting on a stationary wing /in free air/ is always smaller than the propeller thrust. If, however, a jet flap or blowing over a rigid flap are used, an almost perfect slip stream deflection can be achieved; moreover, an induced aerodynamic force originates, so that the resulting force acting on the wing can be greater than the sum of the propeller thrust and the jet reaction force. Fig. 12 gives the results of informative measurements.

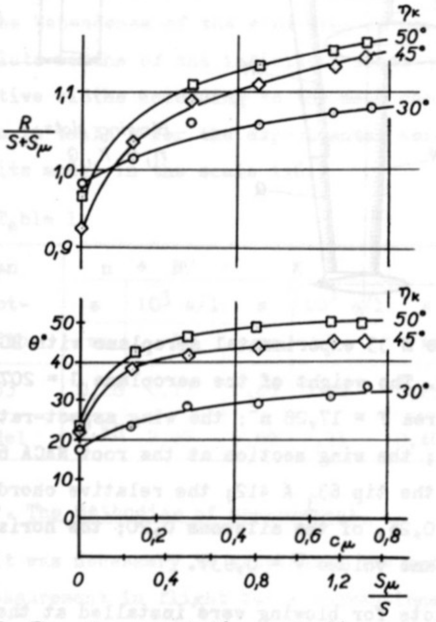


Fig.12. Thrust augmentation and slip stream deflection by blowing over the flap. Section NACA $64_1$212, 13,6% plain flap.

R denotes the resultant force, S the propeller thrust, S_μ the jet reaction force, Θ the angle of slip stream deflection. Apparently, a "thrust augmentation" by as much as 15 per cent was achieved.

With application to aeroplane model the following conclusions were made: By addition of propellers running at zero thrust to the model, the aeroplane lift, expecially maximum lift, was diminished. With growing propeller thrust coefficient the lift was restored /approximately at $T_c = 1,5$/ and increased with further increasing thrust. But the possibility of using the propeller thrust and slip stream deflection in order to shorten the landing was not confirmed by measurements on the aeroplane model, because, even at large flap deflections /75°/, the propeller thrust prevailed over the induced resistance and did not allow for a descent of the aircraft at a sufficiently steep angle.

7. A note on the model design.

The main problem with blown models in wind tunnel is the supply of compressed air into the model. The connection between the pipeline and the model must not exert any forces upon the model, in order not to disturb the weighing of aerodynamic forces; on the other hand, it must allow for small displacements of the model, which are necessary during weighing. An entirely satisfactory solution was found in the use of two metal bellows, which are connected by telescopic tubes. One of the bellows is attached to the inlet into the model, the other one to the rigid supply pipeline. The two bellows represent a sort of flexible joints, the telescopic tubes serving to take up the dilatation of the bellows under the action of an overpressure in the pipeline, and permit the model to be rotated about the axis of the pipeline. The connection is illustrated in fig. 13. (The lower bellow is not seen).

An unusual conception has been adopted for the model of a large rectangular wing /0,6m x 1,2m/ with a slotted flap between large end-plates /1,75m x 1,75m/. The model could be rotated about the axis of the flap, into which the air inlet entered. The basic part of the wing could be displaced relatively to the flap in both the horizontal and the vertical direction. The model was suspended on strain gauge balances housed in the end-plates. All displacements of the model and the change of angle of attack were

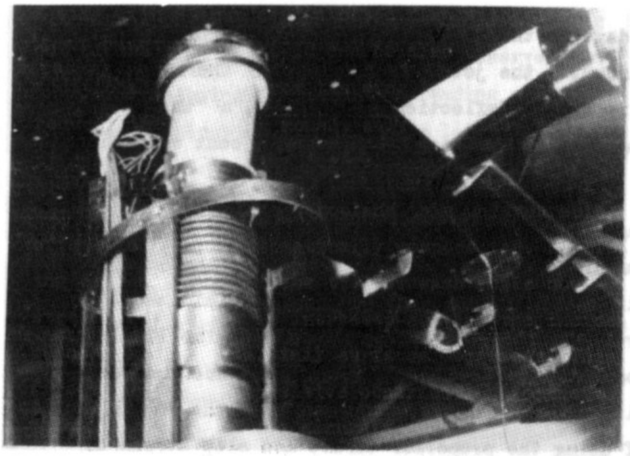


Fig. 13. Flexible connection between model and supply pipe.

performed by built-in electric motors with remote control and reading. A part of the inlet air was branched into the wing nose. - This arrangement enabled a rapid finding of the optimal positions of the flap relatively to the basic part of the wing.

II. Some results of flight investigation on the E 33 experimental aeroplane with BLC by blowing.

/by V. Kočka/

1. The E 33 experimental aeroplane.

The practical use of BLC by blowing to shorten the take-off and landing distance appears advantageous at aeroplanes with jet propulsion and thin wings, at which the ratio of the thrust of jet-engines to the aeroplane weight is greater than 0,35. To perform the considered investigation of blowing in flight, in spite of that said above, there was adapted a small transport aeroplane "Morava L 200" provided with two piston-engines "Walter Minor 6-III" (maximum power 160hp at 2500 rpm) and with variable-pitch propellers of 1,9 meter diameter.

There were two reasons for this choise: Firstly the flight measurements were to be used to gain fundamental information about the effect of blowing on the aerodynamic characteristics of the aeroplane and on its flying qualities and not to find out the optimal design of an STOL aeroplane. Secondly the elected aeroplane made possible its relatively easy rebuilding to an aeroplane with BLC by blowing and a cheap and easy flight measurements of the given type.

On the L 200 aeroplane there was adapted a wing for blowing, further the rear part of the fuselage and the tailplanes with regard to the supposed small speeds and great angles-of-attack, see fig. 1. Into the passanger cabin there was installed a compressor-unit, which delivered 1,6 kg/s of air with the absolute pressure of 2,2 kp/cm^2 at the atmospheric pressure of 735 torr and temperature 15°C.

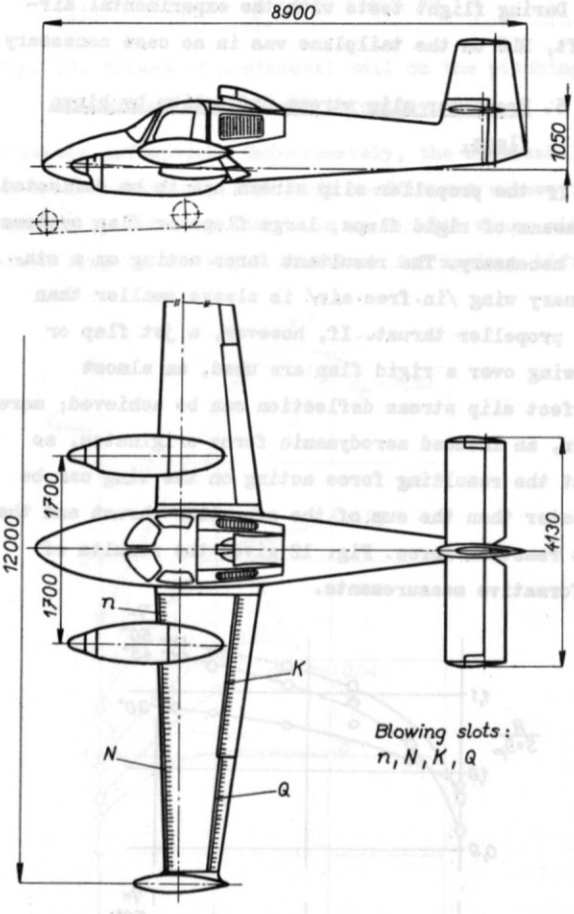


Fig. 1. The E 33 experimental aeroplane with BLC by blowing. The weight of the aeroplane G = 2072 kg; the wing area F = 17,28 m^2; the wing aspect-ratio $\Lambda = 8,35$; the wing section at the root NACA 63_3 A 417, at the tip 63_3 A 412; the relative chord of the flaps 0,25, of the ailerons 0,20; the horizontal tailplane volume $\bar{V} = 0,937$.

The slots for blowing were installed at the leading edge of the wing in 0,5% of its chord between the fuselage and the engine nacelles (the slot notation "n") and between the nacelles and

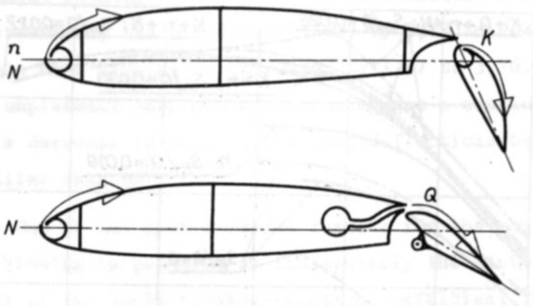


Fig.2. The diagram of the slots for blowing on the wing.

the wing tips (the slot notation "N"), further at the leading edge of the sletted flap in 0,5% of its chord (the slot notation "K") and finally at the tip of the upper part of the wing in front of the aileron (the slot notation "Q"), see fig. 2. Besides the slotted flap there was used also a plain flap, with regard to the simple make, on which it was blown from a slot at the tip of the upper part of the wing in front of the flap (likewise as at the aileron). It was possible to deflect the flaps in the range from 0 to 73° and the both ailerons symmetrically downward in the range from 0 to 30°. The distribution of the reaction of the blown air in the slots K, Q, n and N was approximately in the ratio 4:1:1:3,5. It was possible to set out of work the individual blowing slots on the ground. The used simple type of slots design had an disadvantage of the dependence of the slot area on pressure. The absolute widths of the individual slots s and the relative widths according to the mean chord s/l are shown in table 1 for the experimental aeroplane and for its model in the scale 1:6.

Table 1.

Mean slot-width	n + N		K		Q	
	s	10^3 s/l	s	10^3 s/l	s	10^3 s/l
	mm	1	mm	1	mm	1
E 33	0,26	0,17	0,43	0,28	0,25	0,22
Model	0,58	2,97	0,60	2,31	0,40	1,60

2. The methodics of measurement.

It was necessary to supplement the methodics of measurement in flight for a conventional aeroplane by the measurement of quantities, which determine the condition of the blowing system, and to arrange the measurement in according to a suitable characteristic parametr of blowing.

At wind-tunnel measurements the blowing condition is usually determined by the blown-jet momentum coefficient $c_\mu = \frac{m_\mu . v_\mu}{qF}$, which in the subcritical stream in slots is identical with the blowing reaction coffecient $c_\mu = \frac{S_\mu}{qF}$. In these definitions the term meaning is the following: m_μ is the mass flow through the slot in a second, v_μ is the gas-velocity in the slot, S_μ is the stream-reaction in the slot, q is the kinetic pressure of the aeroplane, and F is the aeroplane-wing area. At steady-flights measurements with an aeroplane which has a separate source of blown-gas independent from flight-velocity, it proved easier to keep a constant value of the parameter S_μ/G = const at different flight-velocities than that of c_μ = const. To compare the results of wind-tunnel measurements at c_μ = const with the results of flight measurement at S_μ/G = const the relation

$$\frac{S_\mu}{G} = \frac{c_\mu}{c_A} \tag{1}$$

is used.

It is impossible to measure both the thrust of individual slots and the total thrust of all the slots directly in flight. To determine the thrust at the subcritical stream in slots ($p_{0\mu}/p_H < 1{,}893$) there was used the expression

$$S_\mu = p_H \frac{k}{k-1} \left[\left(\frac{p_{0\mu}}{p_H} \right)^{\frac{k-1}{k}} - 1 \right] . F_\mu = m_\mu F_\mu \quad , \tag{2}$$

where p_H is the static pressure of the undisturbed air, k = 1,400 (the adiabatic coefficient), $p_{0\mu}$ is the total pressure in the slot and F_μ is the slot area. In flight there was measured the static pressure p_H and the total pressure p_{0v} in both the individual supplying pipes and behind the compressor. The pressures $p_{0\mu}$ and the areas F_μ were determined from the relations $p_{0\mu}\left(\frac{p_{0v}}{p_H}\right)$ and $F_\mu\left(\frac{p_{0v}}{p_H}\right)$, which were stated by measurements on the ground. The imperfection was that the static pressure at the slots in flight was different from that on the ground.

In steady flights a method of saw-type flights was used in surroundings of a constant static pressure p_H at some given constant values of the total pressure p_{0v} behind the compressor (the effect of the aeroplane-weight changes was neglected). In unsteady flights the process was more complicated. At repeated measurements during one flight there followed from the requirement to keep constant the values of the Newton and Froude numbers and the

ratio S_μ/G that it was necessary at a constant initial velocity of flight to increase the density height according to the deminishing weight of the aeroplane.

To state the restitution coefficient of the blowing momentum $c_{\mu r}$ at the lift flap there were used photos of trifts bonded over the whole area of the flaps.

3. <u>The results of measurements in steady flight</u>.

The dependence of the lift coefficient on the angle of attack is shown on the fig. 3. at the flaps deflections η_K = 0 and 60°, at the symmetrical deflection of ailerons ξ_0 = 10° and at the blowing from the slots K, Q, n, N in different combinations at a constant maximum compressor power, at which a reliably superrestitution flow over the lifting flap was attained. The propellers were feathered. With the zero angle of attack the blowing effect appeared as the most expressive when having blown on the lift flap, where the ratio S_μ/G = 0,019 was achieved. The maximum value of the lift coefficient has increased by 0,30 to 1,86 at the slotted flap in the position "a" (ξ_s = -1,22%, η_s = 1,66%). The use of blowing at the leading edge of the wing between the fuselage and the nacelles prevented a stall of this part of the wing and increased in this way the lift coefficient by another 0,30 to 2,16 the maximum angle of attack having been steadily 12,5°. When the blowing at the leading edge outside of nacelles was added, the coefficient $c_{A\,max}$ increased only by 0,11 at the angle of attack value 21°, but the top of the lift curve become flat. It was possible to achieve angles of attack untill 30° without a stall of the aeroplane took place. The blowing at the ailerons at ξ_0 = 10° increased the lift coefficient only by 0,02. When having blown from all the slots the maximum value $c_{A\,max}$ = 2,29 was reached. In this case the distribution of S_μ/G on the slots K, Q, n, N corresponding to the total value S_μ/G = 0,026, was 0,011, 0,003, 0003 and 0,009, and the distribution of the blowing reaction coefficient c_μ = 0,060 at $c_{A\,max}$ on the individual slots was 0,016, 0,007, 0,008 and 0,020. The flaps deflected further to 73° and the ailerons to 20° did not produce any substancial increase of the lift.

In fig. 3 there is drawn also the lift curve at blowing from all the slots, the slotted flap being in the optimum position " *b* ". (ξ_s = 1,00%, η_s = 0,25%), which was found out by measuring in a wind-tunnel on a big model. Further a lift curve of a plain flap is given, which is more advantageous from the design and work points of view than the slotted flap. In the first case the value $c_{A\,max}$ = 2,35 was achieved, in the second case this value was diminished only by 0,12 to $c_{A\,max}$ = 2,17.

The substancially higher increments of the lif-coefficient were achieved when blowing was used at the full propeller thrust for to deflect the slip stream by the flap, see fig. 4.

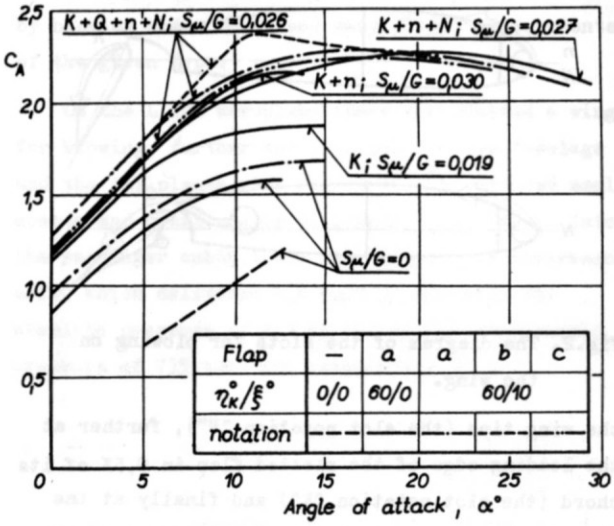


Fig.3. The effect of the wing configuration and of the blowing from different slots on the lift curve $c_A(\alpha)$.
"a", " *b* " - the slotted flaps, "c" - the plain flap.

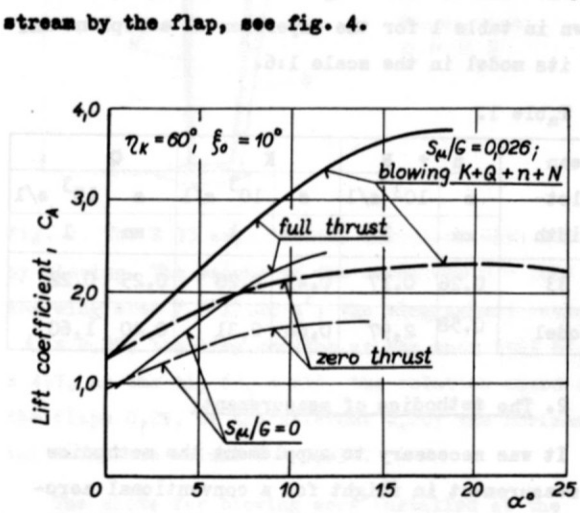


Fig. 4. The effect of blowing on the slip stream deflection.

Without blowing the maximum lift coefficient was increased by the propeller-effect by 0,77 to 2,44, while when blowing it increased by 1,47 to 3,76. An unpleasant phenomenom at landing was a considerable decrease of drag at the flap-deflections being smaller than 90°.

One of the most worthful results for the use of blowing in practise is indisputably the statement of the local blowing-reaction coefficient $c'_{\mu r}$ at different deflections of flaps. The results in fig. 5 agree well with results of measurements being achieved abroad and they show clearly relatively narrow slots to be advantageous to achieve the restitution. At the flaps deflection 60° there was the value $c'_{\mu r}$ = 0,021 ($c_{\mu r}$ = 0,011), i.e. approximately six times smaller than when measured in a wing-tunnel on a model, where relative width of slots was about ten times greater.

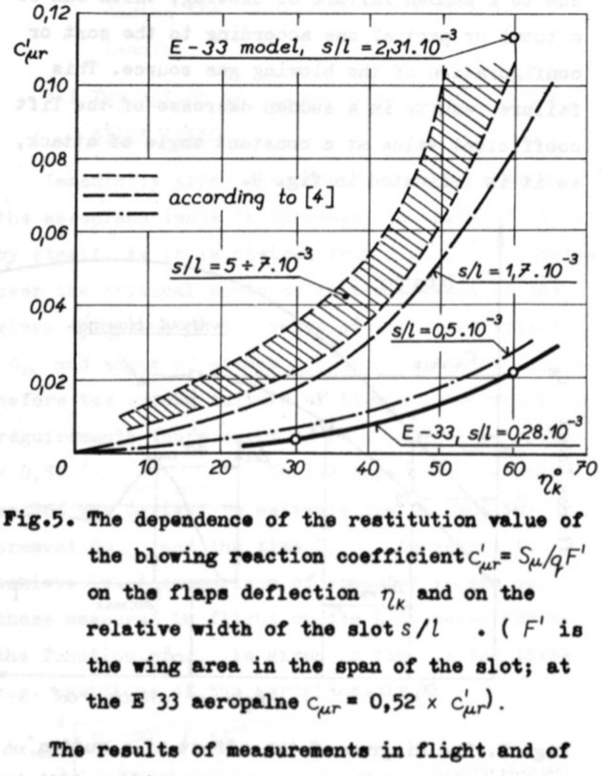


Fig.5. The dependence of the restitution value of the blowing reaction coefficient $c'_{\mu r} = S_\mu / q F'$ on the flaps deflection η_K and on the relative width of the slot s/l . (F' is the wing area in the span of the slot; at the E 33 aeropalne $c_{\mu r}$ = 0,52 × $c'_{\mu r}$).

The results of measurements in flight and of those in a wind-tunnel on a model are compared in fig. 6. The deflection of flaps was 60° and of ailerons ξ_0 = 0. It was blown only from the flap, the relative thrust of the slot being S_μ/G = 0,019. The popellers were feathered. The maximum lift-coefficient value at blowing was higher in flight than on the model by 38%, and without blowing only by 19%. These differences are probably due to the differences of relative widths of slots and of Reynolds numbers (in flight: s/l = 0,28x10^{-3}; Re = 3,0x10^{6}; on the model : s/l = 2,31x10^{-3}; Re = 0,25x 10^{6}). The differences in drag-coefficient values were not yet fairly explained.

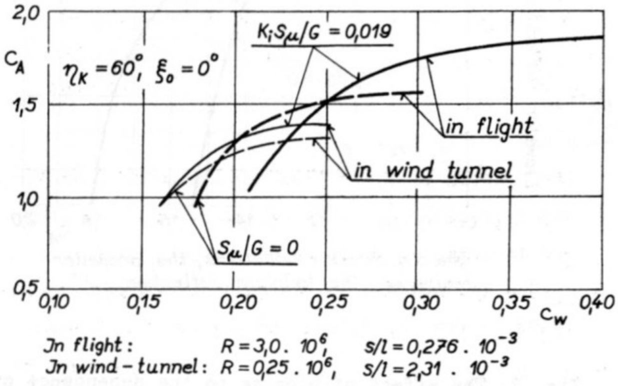


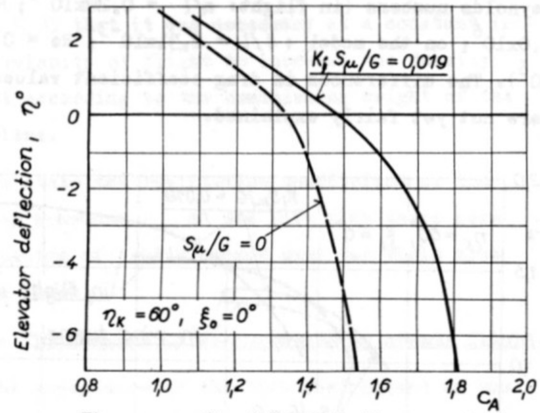
Fig. 6. A comparison of the dependence of lift and drag coefficients measured in flight and in a wind-tunnel.

The deflection of the lift flaps is of a fundamental importance on the static effect of the elevator. It makes a great downwash in the area of the horizontal tail surfaces. The effect of blowing is relatively small. This can be seen from the dependence of the elevator deflection on the lift coefficient in fig. 7. The negative increment of the pitching moment of the wing by blowing was compensated considerably by the effect of down wash on the horizontal tail surfaces, which was called out by the restitution of potential stream on the flap by blowing. From the chart it is obvious as well an unfavourable influence of the downwash behind the wing, the horizontal tail-surfaces getting into it already at small values of angle-attack 7° to 9°, as it was proved by measurements of the down wash in front of the horizontal tail-surfaces.

4. The results of measurements at unsteady flight.

The measurements at unsteady flight were performed on the aeroplane in glide and with propellers feathered only in one chosen configuration η_K = 60° and ξ_0 = 10° and with blowing from all the slots at the total relative thrusts of slots S_μ/G = 0 and 0,026. When blowing there were chosen three initial flight conditions corresponding to (0,60; 0,85 and 1,0)$c_{A\,max}$.

As to the short-period longitudinal motion of



The c.g. position $x_s/l = 0,283$, the propeller feathered, the tailplain deflection $-2°$.

Fig. 7. The effect of blowing on the dependence of the elevator deflection and the lift coefficient.

the aeroplane the effect of blowing in the linear part of lift-curve and at the mean c.g. position was not substantial. With the increasing value of lift coefficient the damping decreased so that at $C_{A\,max}$ the period was 3,1s and the time to half-amplitude was 4,6s. The effect of blowing on the phugoid motion was not substantial too.

The blowing on ailerons influences favourably their efficiency especially at their maximum deflections so that the rolling moment by ailerons increases by approximately 15 to 20%. To get this increment there was sufficient a very small relative thrust of the slot at ailerons $S_\mu/G = 0,003$ i.e. $S_\mu = 6$kp. The local blowing coefficient $c'_{\mu r} = 0,0145$ was at that time substantially greater than its restitution value 0,0035.

The dependence of ailerons efficiency at small step-deflections is obvious from fig. 8. Without blowing this efficiency tends to decrease with diminishing flight velocity, when blowing this tendency is opposite. When flying at $C_{A\,max}$ there appeared an unfavorable effect of the secondary yawing moment due to ailerons, which was growing with the increasing symmetrical deflection of ailerons ξ_o. At the $C_{A\,max}$ there was not achieved a quasi-steady rolling motion of the aeroplane, this motion being oscillating around a certain mean value.

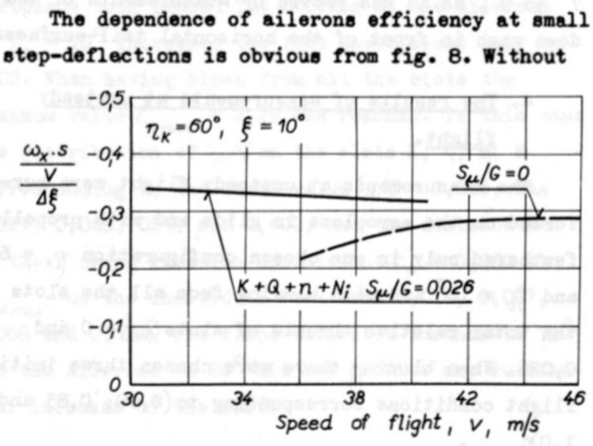


Fig. 8. The effect of blowing on the lateral control.

5. The results of flight investigation of the aeroplane motion after a sudden failure of blowing.

An important problem is the way of practical use of the lift-coefficient increase to shorten the take off and landing distance with regard to present flight requirements and to the crash hazard due to a sudden failure of blowing, which can be a total or partial one according to the sort or configuration of the blowing gas source. This failure results in a sudden decrease of the lift coefficient value at a constant angle of attack, as it is indicated in fig. 9.

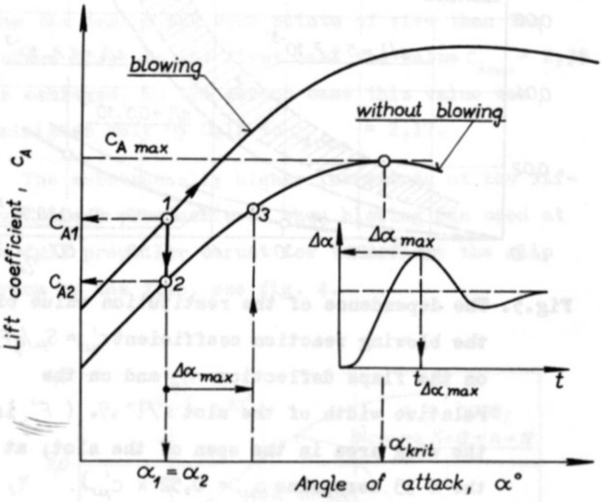


Fig. 9. The diagram of the effect of a sudden failure of blowing on the lift coefficient at stick fixed.

To judge the aeroplane crash hazard there was investigated the aeroplane motion following from a sudden failure of blowing by Šilhánek in ARTI and its results were proved by measurements in flight on E 33 experimental aeroplane. Two phases of this motion were investigated:

a) The motion in a short time interval about 1 sec at the pilot stick fixed. This case corresponds to a lagging pilot response, who did not react at once after the blowing failure.

b) The motion since the blowing failure until the aeroplane reaches the horizontal flight when touching the ground, see. fig. 10, and a control process to get the minimum loss of height Δz necessary for this maneuvre.

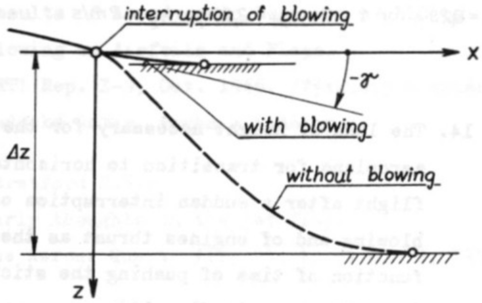


Fig. 10. The diagram of flight paths at landing with blowing and after a blowing failure during the dangerous conditions when landing.

5.1 The motion of the aeroplane with elevator stick fixed.

Immediatly after a sudden failure of blowing the aeroplane tends to increase its angle of attack by itself. As it is obvious from fig. 9 the passing over the critical angle of attack depends at the given aeroplane on the value of lift coefficient c_{A1} and angle of attack α_1 belonging to the flight before the sudden failure of blowing. According to reguirements there ought to be $c_{A1} \leqq (c_{A\,max})_{blow}/1{,}3^2 = 0{,}59\ (c_{A\,max})_{blow}$. In the paper (6) a simple method was derived to estimate the maximum increment $\Delta\alpha_{max}$ and the time $t_{\Delta\alpha_{max}}$ necessary to achieve it. A comparison of computed values and these measured in flight on the E 33 aeroplane as the function of c_{A1} is given in fig. 11 for three c.g. positions of the aeroplane.

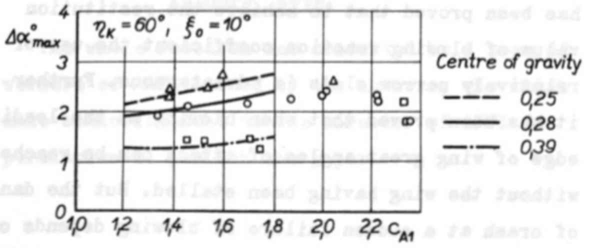


Fig.11. The maximum increments of angle of attack on the E 33 aeroplane as the function of the lift coefficient value before a sudden interruption of blowing.

5.2 The whole controlled motion of the aeroplane after a sudden failure of blowing.

The minimum value of the height loss, called the critical height, depends according fig. 10 on piloting procedure. The way of finding out the optimum control procedure is a variatinal problem of conditional extremum and with the fixed starting point and free terminal point. There is a special condition, that the available values of angle of attack and elevator deflection are limited within of given final interval. To solve this problem in paper (6) there was used after certain simplifying assumptions the general method of "principle of maximum" by L.S. Pontrjagin and the graphic analytical way of solution was proposed.

From the analysis it followed that for the given aeroplane two domains of conditions of landing with blowing exist, which are divided by the critical value of lift coefficient at blowing c_{A1k}. An example of results of theoretical computation for the E 33 aeroplane by the method of the "optimum phase trajectorie" is given in fig. 12, the chosen values of boundaries of lift coefficient without blowing being $c_A = 0$ and 1,64 and the vertical descent velocity being supposed to be 2 m/s at a corresponding power plant output.

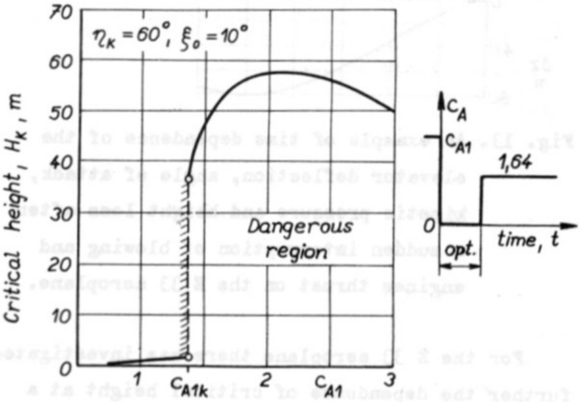


Fig.12. The dependence of critical height for landing on the lift coefficient value before an interruption of blowing and of engines thrust for the E 33 aeroplane.

In the domain of safe conditions for landing at $c_{A1} < c_{A1k}$ the critical height is relatively small (some meters maximum) and to reach a minimum loss of height it is sufficient to increase the angle of attack to maximum simply by pulling the stick, at which a necessary margin of longitudinal maneuvra-

bility is to be kept to perform the transition curved path.

In the domain of the dangerous conditions for landing at $C_{A1} > C_{A1k}$ the critical height values are substantially grater (several tens of metres) than in the first domain. To achieve the minimum loss of height there is necessary to begin with a short pushing the stick to diminish shortly the lift coefficient and to accelerate the aeroplane and then to change the lift coefficient value to its maximum value by pulling the stick, at which a margin of lift remains in order to perform the landing transition.

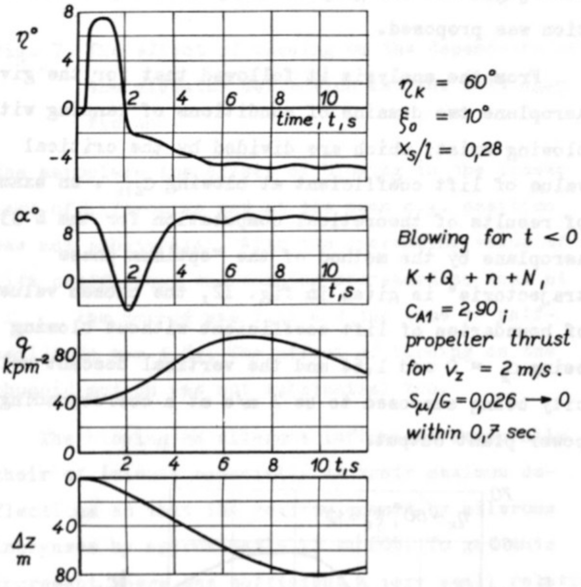


Fig. 13. An example of time dependence of the elevator deflection, angle of attack, kinetic pressure and height loss after a sudden interruption of blowing and engines thrust on the E 33 aeroplane.

For the E 33 aeroplane there was investigated further the dependence of critical height at a given value of lift coefficient before the interruption of blowing C_{A1} on the lenght of time of pushing the stick. Examples of time dependences of the principal values measured in flight are shown in fig. 13, where also the conditions of the experiments are given. These experiments were done in the safe pressure height of 1400m. For these conditions the dependence of the stick-pushing time was small as it can be seen from fig. 14, where is also drawn the result of computed

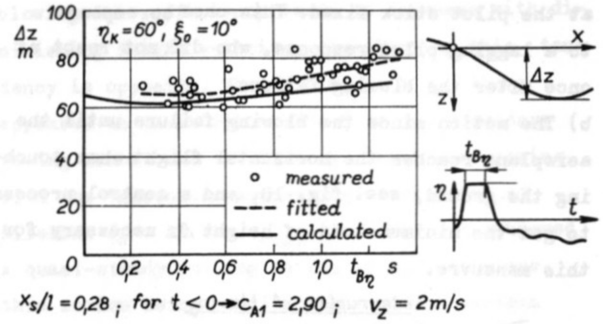


Fig. 14. The loss of height necessary for the E 33 aeroplane for transition to horizontal flight after a sudden interruption of blowing and of engines thrust as the function of time of pushing the stick $t_{B\eta}$ (conditions as in fig. 13).

theoretical curves. The agreement between the computed results and experiments is good.

CONCLUSIONS

In the first part of this paper only some special problems of BLC by blowing were discussed, from which especially the combined blowing and the influence of blowing upon the pitching moment of an aeroplane were important for design of the E 33 experimental aircraft. There was proved in all investigation that the tests performed on relatively small wing models are satistactory for comparison of the efficiency of various arrangements of blowing and for a qualitative study of their aerodynamic properties.

In the second part some results of flight measurements on the E 33 experimental aeroplane are analysed, which are important for exploitation of BLC by blowing to shorten the landing distance. It has been proved that to achieve the restitution value of blowing reaction coefficient the use of relatively narrow slots is advantageous. Further it has been proved that when blowing at the leading edge of wing great angles of attack can be reached without the wing having been stalled. But the danger of crash at a sudden failure of blowing depends on the rate of exploitation of the maximum lift coefficient when blowing at gliding befor landing and on the rate of decrease of blowing intensity at its failure (e.g. at the failure of one source

from several units or only one source). The suggested way of control at a sudden failure of the gas source enables only to reach a minimum value of critical height of landing.

References.

1. Jaňour Z.:
   Results of Aerodynamic Research of BLC by Blowing on Airfoils and Flaps.
   ARTI Rep. Z-9, Oct. 1966. /Výzkumný a zkušební letecký ústav, Praha - Letňany./

2. Stratford B.S.:
   Early thoughts on the jet flap.
   The Aeron. Quart. VII, Pt. 1, p. 45-59, 1956

3. Jaňour Z.:
   Approximate calculation of the lift of a jet-flapped wing.
   Zpravodaj VZLÚ /ARTI/ Nr. 6, pp. 3-6, Prague 1960 /in Czech/.

4. Schlichting, H:
   Aerodynamische Probleme des Höchstauftriebes
   Zeitschrift für Flugwissenschaften, Bd. 13, 1965, Heft 1, S. 1 -14.

5. Tichopád, Vl. - Kočka, Vil.:
   Measurements in flight on the E 33 experimental aeroplane with blowing.
   Internal research report ARTI (in Czech) V-839/66, pp. 169.

6. Šilhánek Vl.:
   Preliminary study of aircraft longitudinal motion after sudden interruption of blowing during take-off and landing. (will be published as ARTI Report).

Author's note.

The whole research was conducted by a team of workers of ARTI headed by the authors, who whish make acknowledgment to the Director of ARTI for permission to publish the paper.