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TRANSONIC FLOW OVER AN AEROFOIL WITH SPOILER

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Experimental tests were made in order to detailed study of two-dimensional flow over an aerofoil with the spoiler. The solid, deflected and slotted spoilers were investigated. The tests were carried out in a transonic wind tunnel at Mach numbers from 0.8 to 1.1 Surface pressure distributions and shadowgraphs were obtained at angles of attack from −4° to 8°. The analysis of the incremental pressure distributions and shadowgraph observations indicated the existence of six regimes of the flow over the aerofoil with spoiler according to the local flow conditions on the aerofoil and to geometric parameters of the spoiler. The lift effectiveness of spoiler defined as the increment of section lift coefficient due to the spoiler is evaluated and its dependence on the test variables is discussed.

Notation

C [mm] aerofoil chord,
C_p pressure coefficient,
C_z section lift coefficient,
h_l [mm] spoiler height,
h_s [mm] slot height,
h_z effective spoiler height,
M_∞ freestream Mach number,
x_l [mm] spoiler location from leading edge of aerofoil,
ΔC_p incremental pressure coefficient due to spoiler,
ΔC_z lift effectiveness of spoiler defined as the increment of section lift coefficient due to the spoiler,
δ_l [°] spoiler inclination angle,
α [°] angle of attack.

1. Introduction

Within recent years, spoilers have been employed for aircraft lateral control on many civil and military aircraft.

Extensive experimental studies have been carried out on spoilers in the 40s, particularly in the United States. The results of these studies are presented in the reports [1, 2]. Rolling moments, yawing moments and hinge moments for the various types of spoilers in incompressible flow are discussed in these reports.

The results of a more recent series of wind-tunnel tests are mentioned in [5], these tests were carried out on various spoiler-slot-deflector arrangements on a swept wing over the Mach number range from 0.6 to 2. It was found that this type of lateral control arrangement is very effective throughout the speed and angle of attack range tested. Unfortunately, the original reports of these tests were not available to the author.

Experimental studies of the spoilers on a flat plate at Mach number 0.6 from to 2.8 were performed by Heyser and Maurer [6]. The streamwise pressure distributions and coefficients of normal and tangential forces are presented.

There are in existence some theories predicting the effects of two-dimensional normal spoilers on the flow over aerofoils in incompressible flow [7, 4, 8, 10, 11]. A very rough theory for the spoiler on the flat plate at supersonic speeds was developed by Seibold [9].

The present experimental study was made in order to determine the effect of the geometric parameters of the various types of two-dimensional spoilers on its lift effectiveness and on the flowfield over the aerofoil at transonic speeds.

2. Model and test conditions

The experiments were conducted in a transonic wind-tunnel of the blow-down type with partial recirculation of the flow. The size of the working section is 0.6×0.6 m. The side walls of the working section are solid and the upper and lower walls are perforated. An open-area ratio was approximately 17 per cent of the upper and the lower surface walls.

The investigation was conducted over a nominal freestream Mach number range from 0.8 to 1.1. The chord Reynolds number varied from $2 \cdot 10^6$ to $4 \cdot 10^6$, respectively to the lower and the upper limits of the Mach number range. The angle of attack was varied in range from $-4°$ to $8°$.

The test model completely spanning the working section was installed between the side walls in the region of the observation windows. The aerofoil was 8% thick. Solid, slotted and deflected spoilers were investigated. The height of the spoilers and of the slots varied from an 0.02 to 0.10 chord and an 0.01 to 0.03 chord, respectively. The chordwise locations of the spoilers varied from an 0.5 to 0.9 chord. The inclination angles of the spoilers were 15°, 30°, 45°, 60° and 90°. The downstream face of each spoiler was machined at its tip to form a 45° knife edge.

Surface pressure distributions at mind-span were made and also shadowgraph observations.

The pressure data were reduced by a computer program which calculated the pressure coefficients and integrated pressure distributions to obtain the lift coefficients. The computer program also calculated the increment of the above quantities due to the spoiler.

3. The effect of the spoiler on the flow over the aerofoil

In order to analyze the affect of the spoiler on the flowfield over the aerofoil, the incremental pressure coefficient was used, which was defined as the difference between the pressure ceofficient in the same point of the aerofoil with and without the spoiler.

Barnes [4] found that in an incompressible flow the spoiler affects the flow over the whole aerofoil and the incremental pressure coefficients are different from zero on both the upper and the lower surface of the aerofoil. On the other hand, in the supersonic flow, the spoiler affects the flow over only some distance upstream and downstream of its location on the upper surface. The incremental pressure coefficients are equal to zero on the remaining part of the upper surface and on the lower surface.

The above description of the spoiler influence on the flow over the aerofoil in the incompressible and the supersonic-flow are presented because the analysis of the incremental pressure distributions indicated the existence of two such basic regimes of the spoiler influence within the range of freestream Mach number from 0.8 to 1.1.

However, after close examination of the incremental pressure distributions and shadowgraph observations, it was found that six different regimes of the flow over an aerofoil with spoiler exist at transonic speeds. These regimes of the flow formed according to the freestream Mach number and the angle of attack (local flow conditions on the aerofoil) and to the geometric parameters of the spoiler.

The regime (A) of the flow appears: when a weak shock wave does not induce a boundary-layer separation on the upper surface of the aerofoil without the spoiler. The spoiler causes the disappearance of the supersonic region on the upper surface and its appearance on the lower surface. This region is terminated by a weak shock wave which moves downstream with the increase of the spoiler height. The incremental pressures are different from zero on the upper and the lower surface. The lower surface incremental pressures are small except at the forward part of the aerofoil where the supersonic region exists.

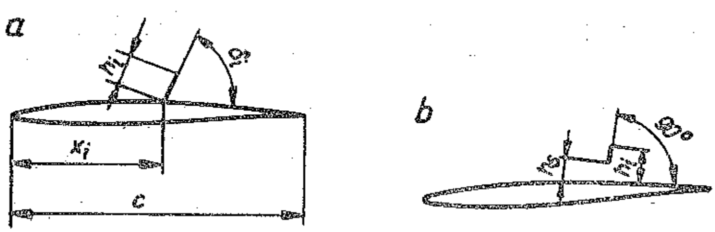

Fig. 1. Sketch of test model geometry
a) solid ($\delta_i=90°$) and deflected ($\delta_i \neq 90$) spoilers, b) slotted spoiler.

The regimes (B1) *or* (B2) of the flow appear according to the geometric parameters of the spoiler, when a strong shock wave separates the boundary layer on the fore of the upper surface.

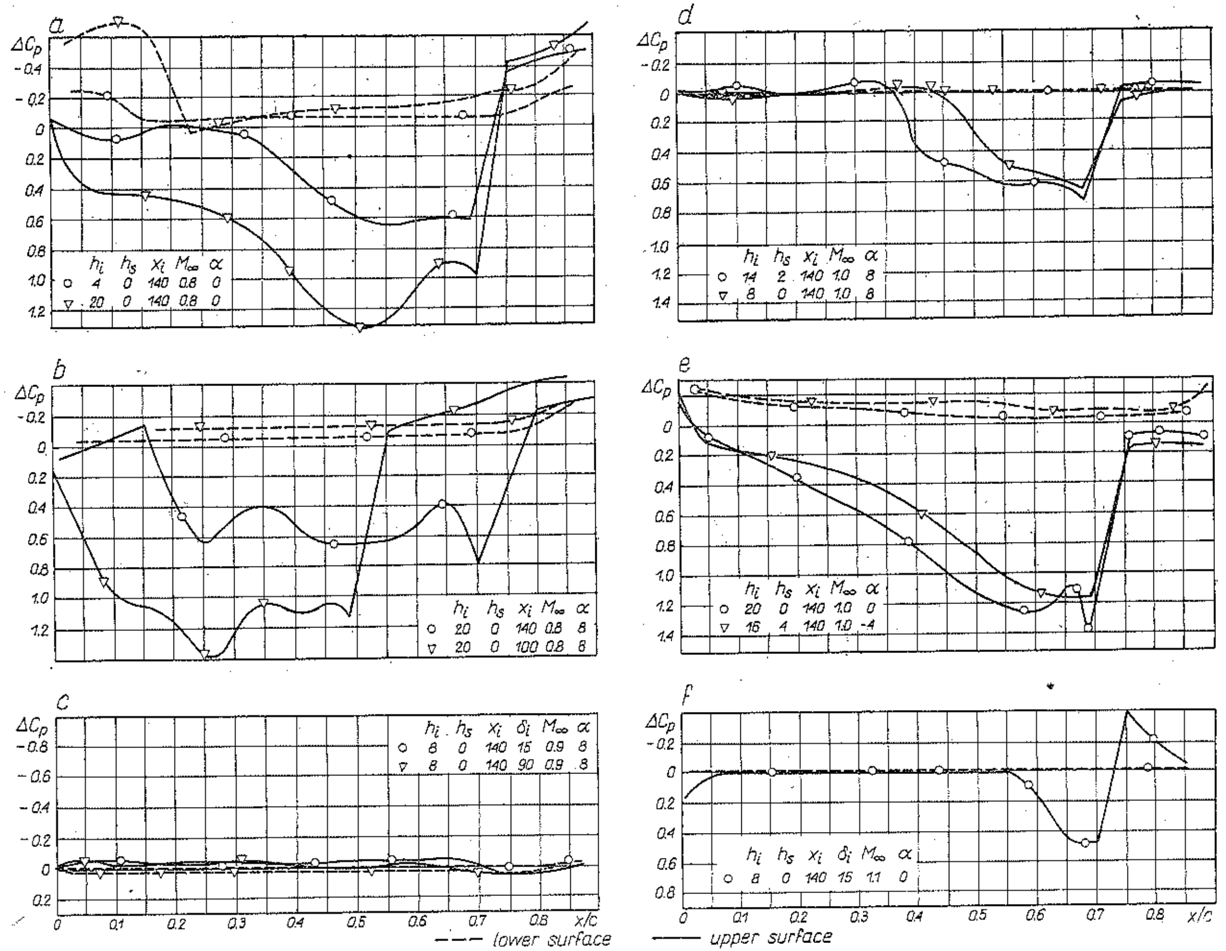

Fig. 2. Typical incremental pressure distributions on the aerofoil with spoiler for different regimes of flow at transonic speeds
a) regime (A); b) regime (B2); c) regime (B1); d) regime (C); e) regime (D); f) regime (E).

The regime (B1) occurs for the narrow spoilers, in that the spoiler does not affect the flow over the aerofoil and the incremental pressures are equal to zero on both the upper and the lower surface as shown in Fig. 2c.

The regime (B2) occurs for the wide spoilers, in that the spoiler causes decreasing or the disappearance of the supersonic region at the upper surface as shown in Fig. 3b. The incremental pressures are different from zero on the upper and approximately equal zero on the lower surface.

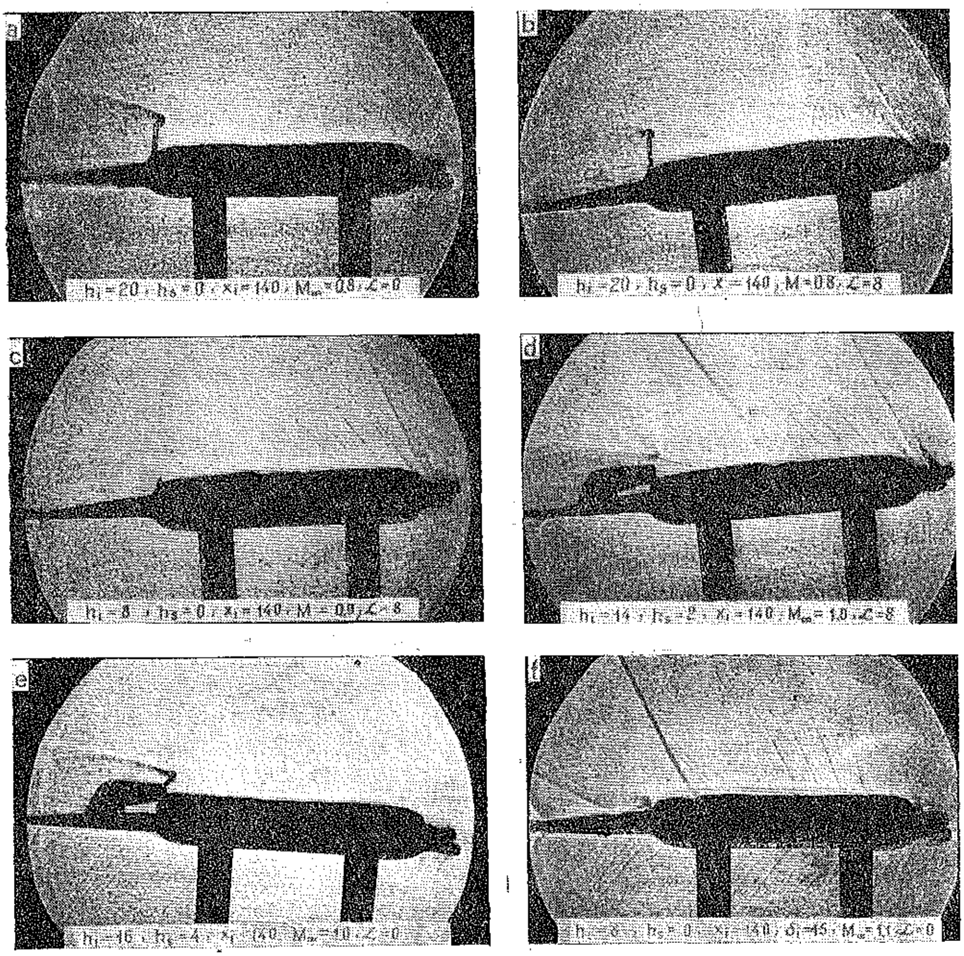

Fig. 3. Typical flowfield over aerofoil with spoiler for different regimes of flow at transonic speeds a) regime (A); b) regime (B2); c) regime (B1); d) regime (C); e) regime (D); f) regime (E).

The regime (C) of the flow appears when a fully supersonic flow exists on the upper and the lower surfaces or the shock wave separates the boundary-layer at the rear end of the aerofoil. The spoiler brings about a decrease of the supersonic region on the upper surface as shown in Fig. 3d. The incremental pressures are different from zero only some distance upstream and downstream of the spoiler.

The regimes (D) of the flow occurs at the same flow conditions on the aerofoil as for the regime (C). The spoiler causes the disappearance of the supersonic region from the upper surface as shown in Fig. 3e.

The incremental pressures are different from zero on both the upper and the lower surface similar to the regime (A). But in contrast with the regime (A) the lower surface incremental pressures are small and approximately constant along the chord (Fig. 2e). In the above-mentioned regimes of the flow the separated-flow downstream of the spoiler does not reattach to the aerofoil. The incremental pressures remain constant along the chord downstream of the spoiler.

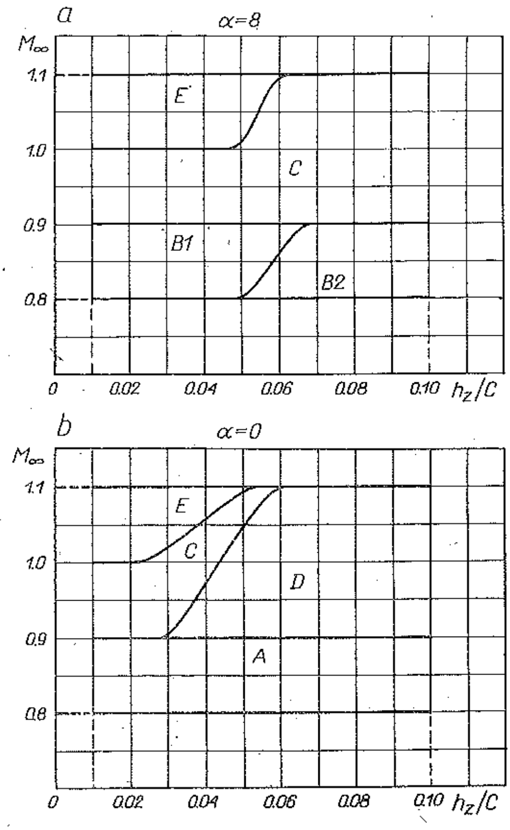

Fig. 4. The approximate boundaries between regimes of flow over aerofoil with spoiler at the location an 0.7 chord.

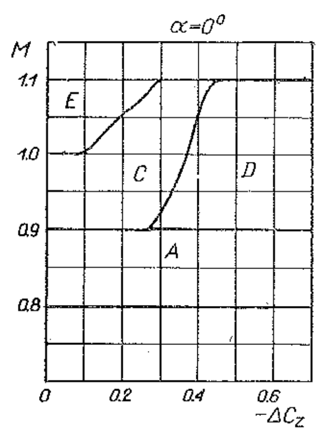

Fig. 5. Correlation of the spoiler lift effectiveness with different regimes of the flow over aerofoil with spoiler.

The regime (E) of the flow occurs: when the fully supersonic flow is developed on the upper and the lower surface. The spoiler causes separation of the boundary-layer upstream and reattachment of the separated flow downstream of the spoiler, similar to the freestream supersonic flow case. The incremental pressures are different from zero only some distance upstream and downstream of the spoiler.

An effective spoiler height h_z was introduced: 1) for the deflected spoilers: $h_z = h_i \sin \delta_i$; 2) for the slotted spoilers: $h_z = h_i - h_s$.

The approximate boundaries between the different regimes of the flow over the aerofoil with the spoiler at an 0.7 chord for the angle of attack of 0° and 8° are shown in terms of the freestream Mach numbers and the effective spoiler height in Fig. 4.

This figure indicates that the above-mentioned regimes of the flow formed in fact according to the local flow conditions on the aerofoil and to the geometric parameters of the spoiler.

In Fig. 5 a correlation of the spoiler lift effectiveness and regimes of the flow over the aerofoil with spoiler for the angle of attack $\alpha = 0°$ may been seen. It was concluded that the above experimentally observed correlation for the three of types of spoiler (solid, slotted and deflected) with different values of their geometric parameters is quite good.

4. Dependence of spoiler lift effectiveness on the geometric parameters of the spoiler

The lift effectiveness of the spoiler was defined as the increment of the lift coefficient due to the spoiler. The lift effectiveness of the spoiler depends on its geometric parameters i.e. on the height, the inclination angle and the location of the spoiler and on the height of the slot in the case of the slotted spoiler.

The dependence of the spoiler lift effectiveness on the spoiler height is shown in Fig. 6. This dependence is approximately linear at the Mach number of 0.8. This dependence becomes less linear with increasing of the Mach number. At Mach number 1.1 in the range of the spoiler height from an 0.02 to an 0.04 chord, the increase of the spoiler lift effectiveness is slight. But in the range from an 0.04 to an 0.06 chord the spoiler lift effectiveness strongly increases with the increase of the spoiler height.

The dependence of the spoiler lift effectiveness on the inclination angle of the spoiler is presented in Fig. 7. This dependence is qualitatively similar at the angle of attack of 0° and −4°.

The spoiler lift effectiveness strongly increases with the increase of the inclination angle up to 60°. But in the range between 60° and 90° the increment of the spoiler lift effectiveness is slight.

The spoiler lift effectiveness is approximately equal to zero at the Mach number of 0.8 and 0.9 and the angle of attack of 8° on account of the appearance of regime (B1) of the flow in this case.

The slotted spoiler lift effectiveness depends on the slot height. This dependence is shown in Fig. 8 for the ratio of the slot height to the spoiler height from 0 to 0.5. The slotted spoiler lift effectiveness decreases approximately linearly with the increase of the slot height at the angle of attack of −4° and 0° and the range of the Mach number from 0.8 to 1.1. But at the angle of attack of 8° the spoiler lift effectiveness is independent of the slot height.

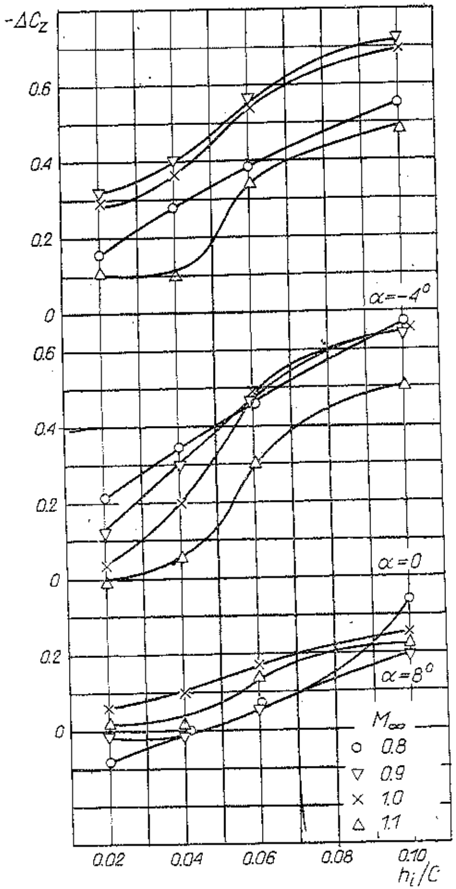

Fig. 6. Influence of spoiler height on spoiler lift effectiveness, location of spoiler of an 0.7 chord

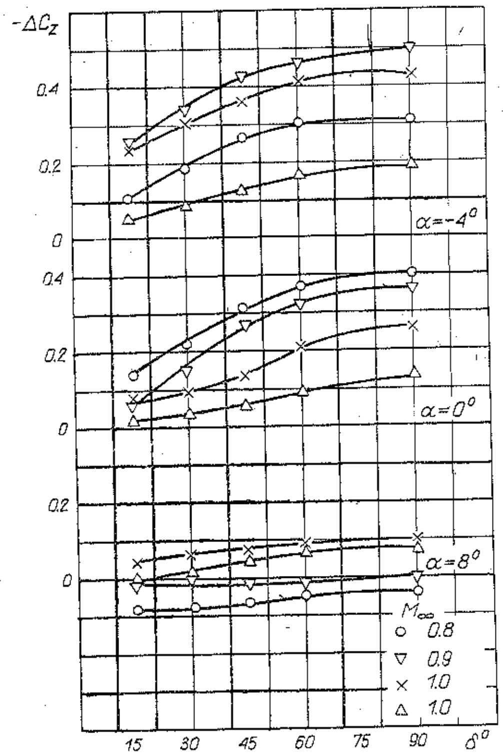

Fig. 7. Influence of spoiler inclination angle on lift effectiveness, location of spoiler of an 0.7 chord.

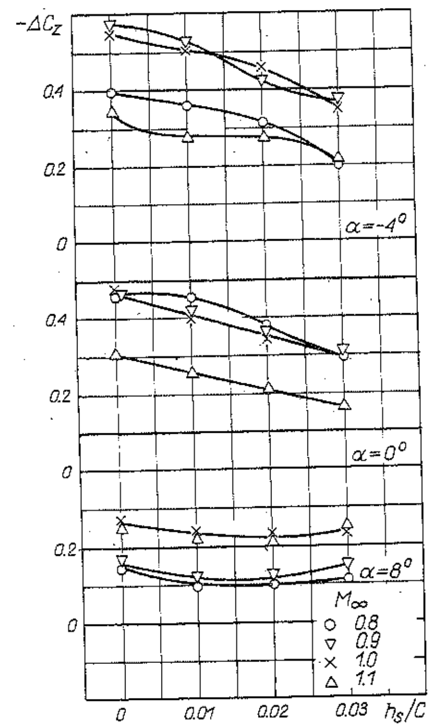

Fig. 8. Influence of slot height on slotted spoiler lift effectiveness, spoiler height of an 0.06 chord and spoiler location an 0.7 chord.

5. The effect of the freestream Mach number on spoiler lift effectiveness

The variation of the spoiler lift effectiveness with the freestream Mach number depends primarily on the angle of attack.

Figure 9 shows this variation at the angles of attack of −4°, 0° and 8° for the solid spoilers. At the angle of attack of −4° the spoiler lift effectiveness increases strongly with the increase of the Mach number up to a maximum value of approximately 0.9 and then decreases. The value of this maximum depends on the geometric parameters of the spoiler. At the angle of attack of 0° the dependence of the spoiler lift effectiveness at the lower Mach numbers is rather slight. At Mach numbers greater than one, depending on the geometric parameters of the spoiler, the lift effectiveness due to the spoiler decreases considerably with the Mach number. At the angle of attack of 8° the spoiler lift effectiveness decreases strongly to zero with the increase of the Mach number up to 0.9 and then slightly increases.

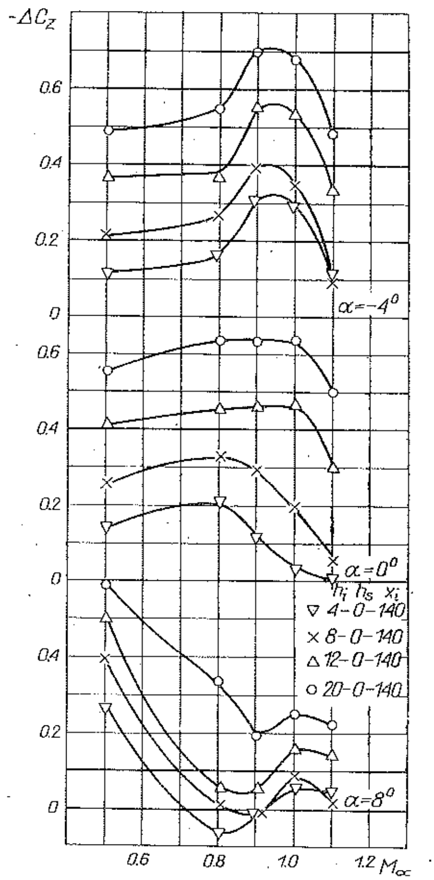

Fig. 9. Dependence of the spoiler lift effectiveness on Mach number for solid spoiler.

6. Conclusions

In this paper has been described the experimental study of three types of spoiler and their geometric parameters effect on the flowfield over the aerofoil and on the lift effectiveness of the spoiler at transonic speeds. The results of this study suggests the existence of six different regimes of the flow over aerofoil with spoiler at a range of Mach number from 0.8 to 1.1 and at angles of attack before stall. The occurence of these regimes of flow is dependent on the local flow conditions on the aerofoil without spoiler and on the geometric parameters of the spoiler. In different regimes of the flow the spoiler effects in various manner on the flow aerofoil. The lift effectiveness of the spoilers are correlated with the regimes of the flow occurring at a given Mach number and angle of attack. The spoiler lift effectiveness varies considerably, depending strongly on the geometric and flow parameters, especially at Mach numbers close to unity.

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Streszczenie

TRANSONICZNY OPŁYW PROFILU Z INTERCEPTOREM

W celu dokonania szczegółowej analizy dwuwymiarowego opływu profilu z interceptorem, przeprowadzono eksperymentalne badania w transonicznym tunelu aerodynamicznym w zakresie liczb Macha od 0,8 do 1,1.

Badano interceptory bez- i ze szczeliną oraz interceptory pochylane. Mierzono rozkład ciśnienia na powierzchni profilu i dokonano wizualizacji przepływu w zakresie kątów natarcia od −4° do 8°. Analizując rozkłady przyrostu ciśnienia i zdjęcia cieniowe przepływu, stwierdzono występowanie sześciu reżimów opływu profilu z interceptorem, w zależności od lokalnych warunków przepływu na profilu bez interceptora.

Określono skuteczność interceptora zmniejszania siły nośnej oraz przedyskutowano zależność skuteczności od badanych zmiennych.

Резюме

ОКОЛОЗВУКОВОЕ ОБТЕКАНИЕ ПРОФИЛЯ С ИНТЕРЦЕПТОРОМ

С целью проведения подробного анализа двумерного обтекания профиля с интерцептором проведены экспериментальные исследования в околозвуковой аэродинамической трубе в интервале чисел Маха от 0,8 до 1,1.

Исследовались интерцепторы без и со щелью, а также наклоненные интерцепторы. Измерялось распределение давления на поверхности профиля и проводилась визуализация течения в интервале углов атаки от −4° до 8°. Анализируя распределения прироста давления и теневые фотоснимки течения констатировано выступание шести режимов обтекания профиля с интерцептором в зависимости от локальных условий течения на профиле без интерцептора.

Определена эффективность интерцептора уменьшения несущей силы, а также обсуждена зависимость эффективности от исследуемых переменных.

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