ROZPRAWY INŻYNIERSKIE • *ENGINEERING TRANSACTIONS* • 35, 2, 217–227, 1987
Polska Akademia Nauk • Instytut Podstawowych Problemów Techniki

A STUDY ON MATCHING PROBLEMS OF SUPERSONIC TWO-DIMENSIONAL AIR INLETS(*)

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In order to ensure a uniform and stable compressor face flow, maximum total pressure recovery and minimum pre-entry drag for an Air Inlet of a supersonic aircraft of flight Mach numbers above 2, over its entire flight range and variable geometry, is a necessity. The variable multi-ramp external compression two-dimensional Air Inlet is one of the most attractive solutions for this case, where variable geometry may be easier to engineer [1]. In this paper two developed computer programs (GMTRY and CRIT) are presented. Oswatitsch [2] optimum ramp angles are used to determine the geometrical shape of the three ramp variable deflection Air Inlet, and the exact solution of the shock wave equation is utilised to determine a number of parameters relevant to the Air Inlet performance at design and critical operational conditions. Flow shape and flow pattern at critical, sub-critical and Ferri limit of the air inlet under study are presented.

NOMENCLATURE

A	capture area,
A_{en}	throat area,
CRIT	computer program predicting Air Inlet critical performance,
CDADD	coefficient of additive drag,
GMTRY	computer program determining Air Inlet geometry,
M	upstream Mach number,
MFR	air mass flow ratio,
MFF	air mass flow function,
P	static pressure,
P_0	total pressure,
P_∞	upstream total pressure,
Q	air mass flow rate per Inlet,
T	static temperature,
TPR	total pressure recovery,
σ	spillage ratio,
δ	ramp deflection angle.

(*) Accepted for the XVII Biennal Fluid Dynamics Symposium, 1–7 September 1985, Warsaw, Poland.

1. Introduction

Oswatitsch [2] noted that high Inlet total pressure recovery at supersonic flight speeds could be achieved by means of compression surfaces generating one or more oblique shock wave (*s*) in front of the Inlet aperture to decelerate the flow ahead of the terminal normal shock wave. Dunham [3] discussed the deviation of Air Inlet operational conditions during take-off, climb, manoeuvre, ... etc., from the design ideal. Hurd [4], pointed out the merits of operating the Air Inlet critically rather than sub or super-critically. Pai [5] introduced mathematical models for the estimation of Air Inlet performance at critical and subcritical operating conditions. Mc Gregor [6] developed some theoretical parameters relevant to the performance of rectangular Air Intakes with double ramp compression surfaces at supersonic speeds. Fakhry [7] published the computer programs developed to estimate the performance of the two-dimensional supersonic Air Inlets.

In this paper, two developed computer programs (GMTRY and CRIT) are presented. Oswatitsch [2] optimum ramp angles are used to determine the geometrical shape of the three ramp variable deflection Air Inlet, and the exact solution of the shock wave equation is utilised to determine a number of parameters relevant to the Air Inlet performance at design and critical operational conditions. Flow shape and flow pattern at critical, sub-critical and Ferri limit of the Air Inlet under study are shown in Fig. 1.

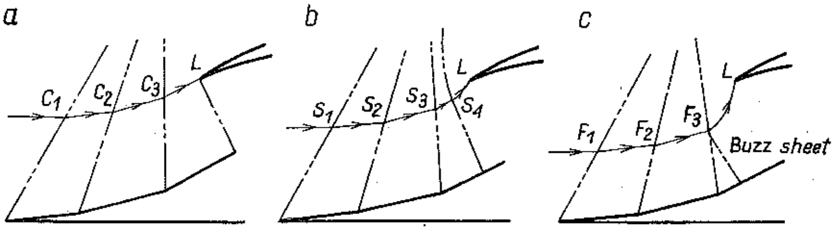

Fig. 1. Critical (subcritical) Ferri conditions. a) Critical flow (normal shock at throat), b) subcritical flow (normal shock expelled), c) Ferri limit (expelled normal shock intersects with previous oblique shock).

A study will follow to determine the performance of the same Air Inlet selected model at subcritical operating condition and to estimate the unstable limiting condition (Ferri limit). Both the present study and the following one may form a solid base for the matching process of Air Inlet and propulsion system.

A trade-off can then be made between the performance improvement at off-design conditions and the increased complexity and weight of a variable geometry Air Inlet.

2. DESIGN CONFIGURATION OF THE PROPOSED AIR INLET MODEL

A computer program GMTRY is developed to determine the geometrical shape of the two-dimensional multi-ramp external compression supersonic

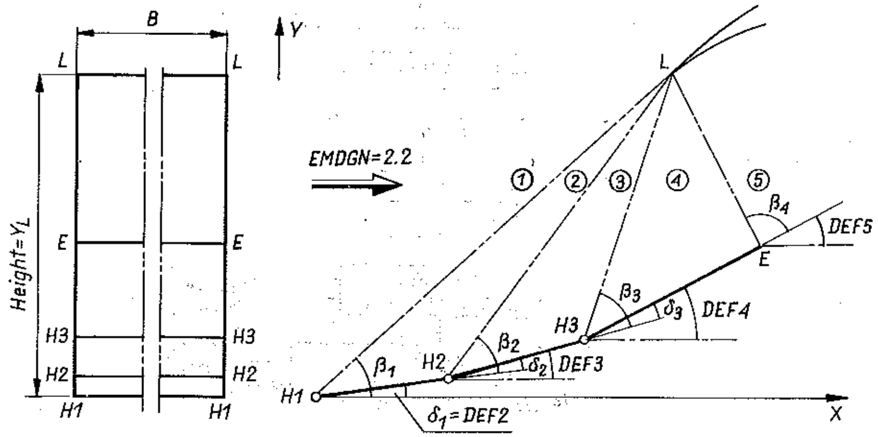

FIG. 2. Design geometry of the proposed Air Inlet model.

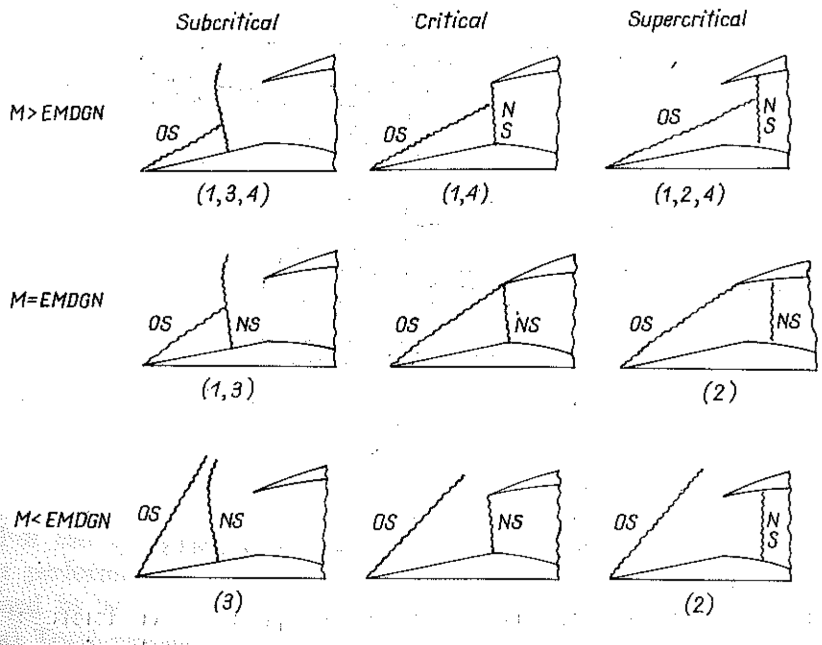

FIG. 3. Shock patterns of a fixed geometry supersonic Air Inlet. *1* — shock intersection; *2* — normal shock ingested; *3* — normal shock expelled; *4* — oblique shock inters lip.

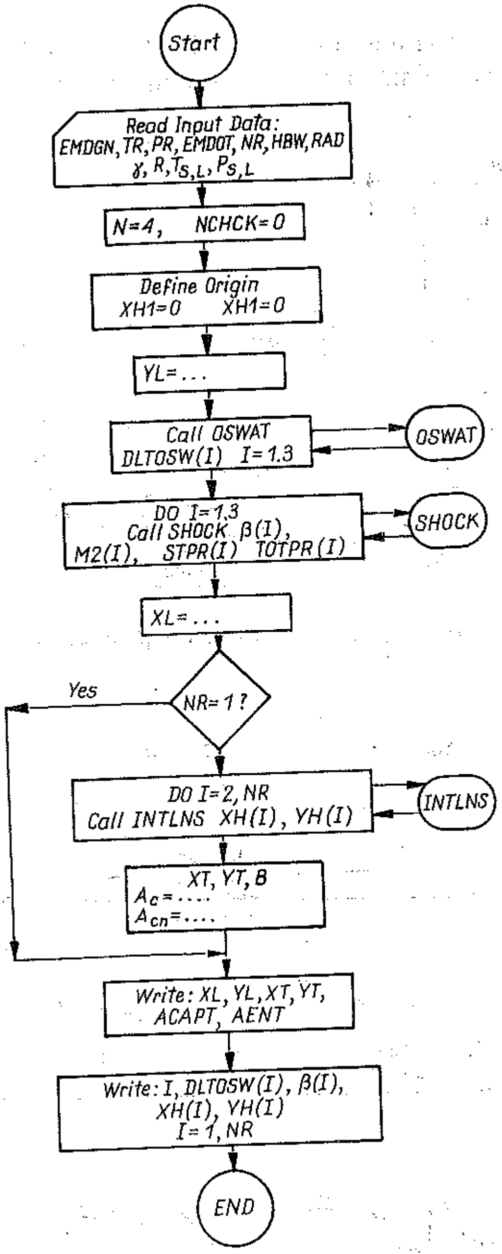

FIG. 4. Flow chart of main program GMTRY.

Air Inlet that matches with a selected design condition (see Fig. 2). This geometry is optimised by fulfilling the following conditions:

All oblique shocks created by the successive ramps are directed to and meet at the outer cowl lip. This ensures zero additive drag and stable outlet flow at design condition.

Design air mass flow rate per Inlet is its critical mass flow. This necessitates that the terminal normal shock is located at duct entry (throat) which minimises Inlet drag and ensures flow stability.

The ramp deflection angles are selected according to Oswatitsch in order to ensure maximum total pressure recovery. A subroutine Oswat was developed to determine these optimum deflection angles for a given number of ramps and design Mach number.

However, the determined Air Inlet geometry can fulfill the above mentioned aspects only at the selected design condition. At off-design conditions (different flight Mach number and/or different air mass flow per Inlet) the shock pattern — if the geometry is fixed-will change (see Fig. 3), with penalties varying from an increase in Inlet drag to a decrease of total pressure recovery or even to unstable flow. Variable geometry is introduced in order to improve the off-design performance.

A flow chart of the developed program GMTRY is shown in Fig. 4.

3. AIR INLET CRITICAL PERFORMANCE

In order to predict the critical performance of the variable ramp Air Inlet at a selected range of flight Mach numbers, a parametric study is carried out (for the geometry determined by the program GMTRY) using a developed computer program CRIT. All the possible combinations of the independent variables M_1, δ_1, δ_2 and δ_3 (with a selected suitable step for each) that produce outlet stable flow are surveyed. The outlet flow is considered stable when: no shock is detached, no shock (*s*) enter (*s*) lip and when no intersection takes place between any of the shocks within the captured stream. Figure 5 shows the flow chart of the developed program CRIT.

4. PARAMETERS DEFINING AIR INLET PERFORMANCE

For this study the following parameters are calculated to define the Air Inlet performance for each operating condition (the operating condition is defined by M_1, δ_1, δ_2 and δ_3).

a) Total pressure recovery (TPR). Defined as the ratio between the total pressure at the delivery end of the Air Inlet to that at the supply end

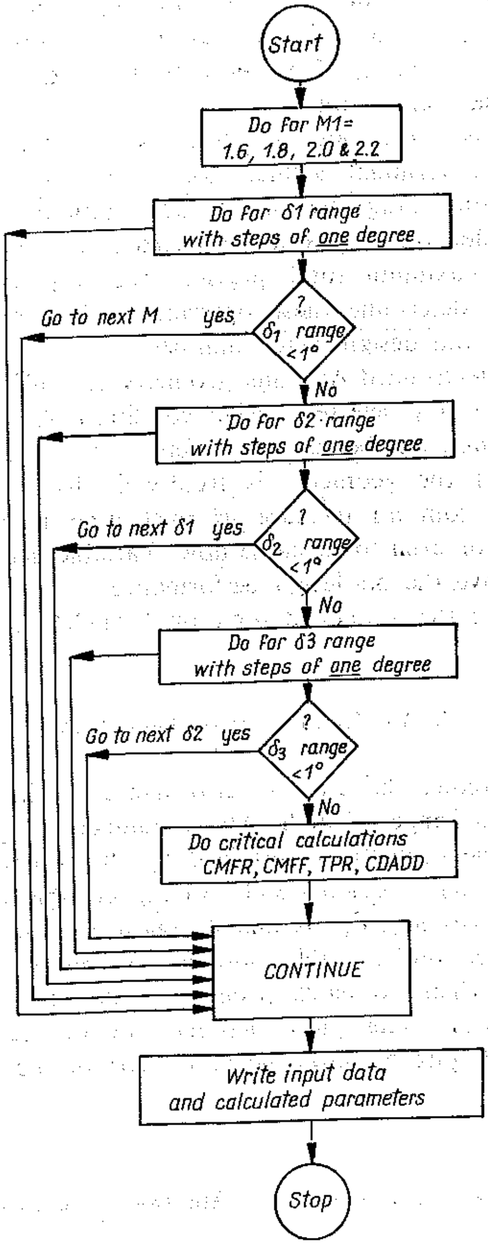

FIG. 5. Flow chart of main program CRIT.

(free stream). In this study only pressure losses due to shock waves are considered. The pressure losses within the subsonic duct are comparatively small. From Fig. 2

$$\mathrm{TPR} = \frac{P_{05}}{P_{01}} = \frac{P_{05}}{P_{04}} \frac{P_{04}}{P_{03}} \frac{P_{03}}{P_{02}} \frac{P_{02}}{P_{01}}$$

product of total pressure ratios across the successive shocks.

A subroutine (SHOCK) is developed to solve the shock wave equation for a given Mach number and deflection angle.

b) Air mass flow ratio (MFR). Defined as the ratio between the operating air mass flow and the maximum geometrically possible air mass flow. From Fig. 1

for critical operation $\mathrm{MFR} = \mathrm{YCl/YL}$,
for subcritical operation $\mathrm{MFR} = \mathrm{YSl/YL}$.

c) Mass flow function (MFF). Engine air flow requirements are usually expressed in the reduced form $Q\sqrt{T_0/P_0}$. It is made effectively nondimensional by dividing by Inlet entry area A_{en}. It can be proved (taking $\gamma = 1.4$) that

$$\mathrm{MFF} = \frac{0.6849\,M^2}{(1+0.2M^2)^3} \frac{\mathrm{MFR}}{\mathrm{TPR}}.$$

d) Coefficient of additive drag (CDADD). The drag force on the outermost stream line is (see Fig. 1b)

$$D = \sum_{n=1}^{NR} (\mathrm{YC}_{n+1} - \mathrm{YC}_n)(P_{n+1} - P_1)$$

and the coefficient of additive drag is given by

$$\mathrm{CDADD} = D \Big/ \left(\frac{1}{2}\gamma M^2 P_1\,\mathrm{YL}\right).$$

5. Results

A pilot study was done on a selected supersonic two-dimensional triple ramp external compression Air Inlet model at the following design conditions (see Fig. 2):

number of ramps (NR) = 3 (all variable),
design flight Mach number = 2.2,
air mass flow rate/INLET = 50 Kg/s,

width/height ratio = 1.0,
design is done at sea level.

The two programs GMTRY and CRIT were tried for this Inlet model and the obtained results were as follows:

a) Output results of program GMTRY (Tabl. 1).

Table 1. Results of main program GMTRY

XL = 0.3398 YL = 0.2335
XT = 0.3980 YT = 0.1245
Capture area = 0.0545
Duct entry area = 0.0288

Hing NO	Defl. angle	Shock angle	XH	YH
1	8.7000	34.4973	0.0000	0.0000
2	9.5000	41.5721	0.1670	0.0256
3	9.9000	54.0423	0.2857	0.0646

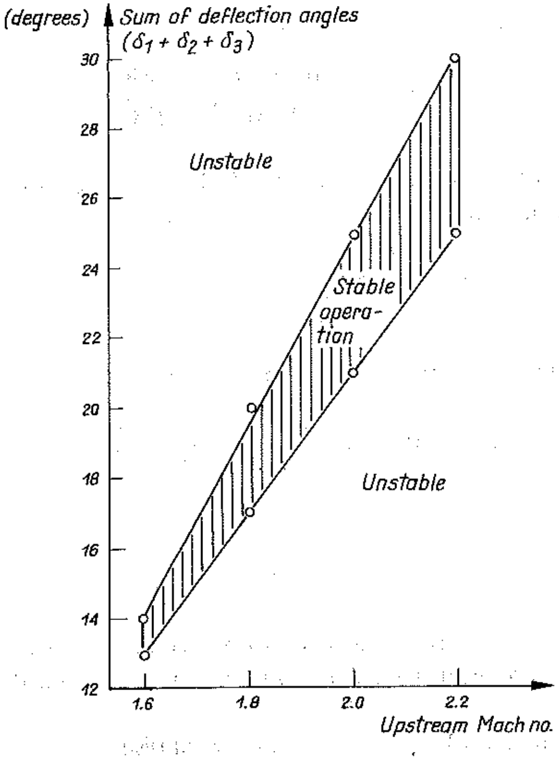

FIG. 6. Sum of deflection angles for stable operation.

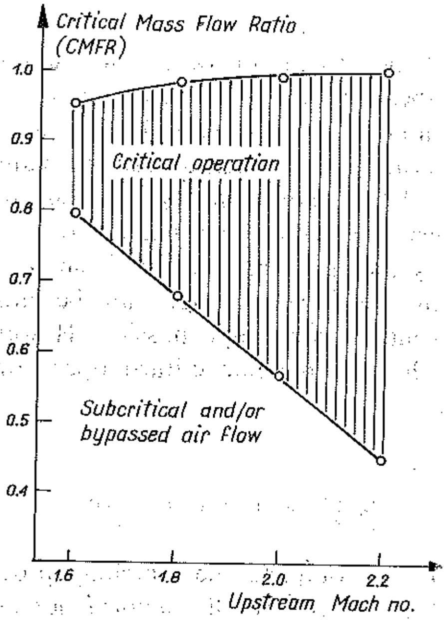

FIG. 7. Range of critical mass flow ratio.

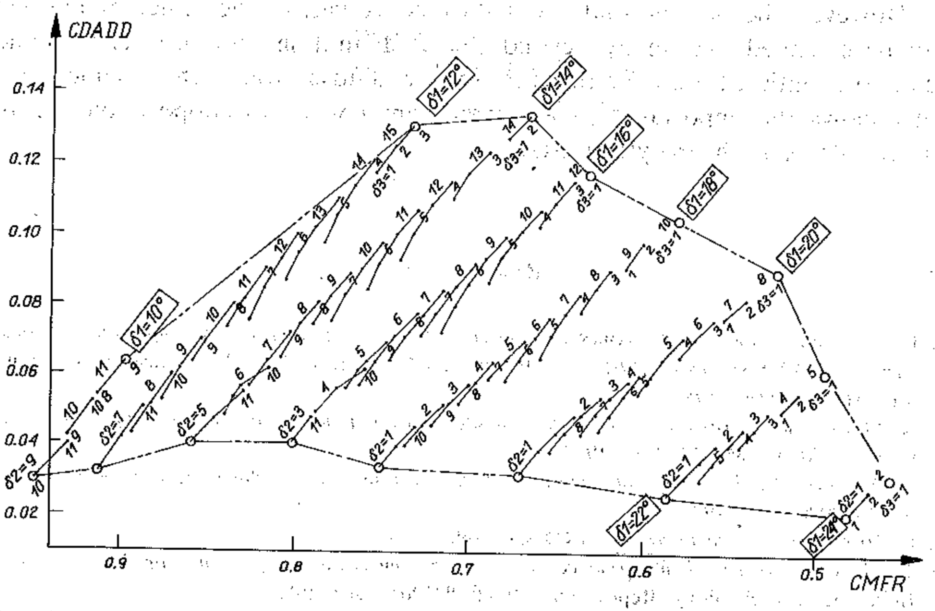

FIG. 8. Air Inlet critical performance, ML = 2.2, δ_1 — marked beside each group, δ_2 — marked above each line; δ_3 — marked below first point.

b) The range of stable critical operation of the proposed Inlet model at various Mach numbers is shown in Figs. 6 and 7 with respect to the total deflection angle and critical air mass flow ratio respectively.

c) The Air Inlet critical performance (can be named Air Inlet map) at the Mach number 2.2 is shown in Fig. 8. The coefficient of additive drag is plotted against the critical air mass flow ratio for all possible combinations of δ_1, δ_2 and δ_3. This map and similar maps for all flight Mach numbers within the aircraft range can be utilised to define the optimum Air Inlet layout for each flight mission. However, for an air mass flow rate lower than that for possible critical operation, the Air Inlet has to work subcritically.

6. CONCLUDING REMARKS

In order to be able to complete the matching process of the Air Inlet and the propulsion engine efficiently, the performance of the two units must be completely known. The present study outlined a method to find out the Air Inlet performance at design and critical operational modes, and a further study must follow to find out the Air Inlet performance at subcritical operational mode.

However, the present study is slightly conservative since Inlet operations can be extended marginally beyond the used limiting criterion, as in some cases the initiated flow perturbations may diffuse before the engine face. This shows the importance of an experimental work to support and verify the results of such analytical study.

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STRESZCZENIE

BADANIA NAD KONSTRUKCJĄ NADKRYTYCZNYCH DWUWYMIAROWYCH CHWYTÓW POWIETRZA

W celu uzyskania jednostajnego i stabilnego przepływu na powierzchni, na której następuje wzrost ciśnienia, w naddźwiękowych samolotach przy liczbie Macha powyżej 2 konieczny jest maksymalny całkowity odzysk ciśnienia i minimalny wstępny opór wlotów powietrza w całym obszarze lotu i dla zmiennej geometrii. Najatrakcyjniejszym rozwiązaniem tego problemu jest użycie wielopłaszczyznowych dwuwymiarowych wlotów powietrza, dla których można łatwo uwzględnić zmienną geometrię. W pracy przedstawiono dwa programy komputerowe (GMTRY i CRIT). Wykorzystano optymalne kąty płaszczyzn znalezione przez OSWATITSCHA [2] w celu określenia geometrycznego kształtu trójpłaszczyznowego chwytu powietrza o zmiennym nachyleniu. Dokładne rozwiązanie równania fali uderzeniowej zostało wykorzystane do znalezienia liczby parametrów istotnych dla wydajności konstruowanego chwytu powietrza i krytycznych warunków pracy. Przedstawiono kształty przepływu w badanych chwytach powietrza dla przepływów krytycznych, podkrytycznych i granicy Ferriego.

РЕЗЮМЕ

ИССЛЕДОВАНИЯ КОНСТРУКЦИИ СВЕРХКРИТИЧЕСКИХ ДВУМЕРНЫХ ВОЗДУХОЗАБОРНИКОВ

С целью получения равномерного и стабильного течения на поверхности, на которой наступает ост давления, в сверхзвуковых самолетах, при числе Маха свыше 2, необходимо максимальное полное восстановление давления и минимальное предварительное сопротивление впусков воздуха в целой области полета и для переменной геометрии. Наиболее интересным решением этой проблемы является использование многоплоскостных двумерных впусков воздуха, для которых можно легко учитывать переменную геометрию.

В работе представлены две программы для компьютеров (GMTRY и CRIT). Использованы оптимальные углы плоскостей, найденные Освагишом [2], с целью определения геометрической формы трехплоскостного воздухозаборника с переменным наклоном. Точное решение уравнения ударной волны использовано для нахождения числа параметров существенных для эффективности построенного воздусозаборника и критических условий работы. Представлены формы течения в иследуемых воздухозаборниках для критических и доктритических течений, а также для предела Ферри.

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Received October 17, 1985.