AerospaceEurope Conference2021
WARSAW, POLAND | 23 -26 NOVEMBER 2021
PSAA
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Council of European Aerospace Societies

PRELIMINARY DESIGN OF A SUPERSONIC PASSENGER AIRCRAFT

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Abstract

This work will discuss the basic issues and problems related to the design of aircraft geometry to be as economical, durable and functional as possible during flights at speeds greater than the speed of sound.

The aim of the work is to create a design for a supersonic passenger plane capable of carrying at least 200 passengers and reaching at least twice the speed of sound. Analysis of the influence of geometrical parameters of airfoils, airfoils adapted to supersonic flights and aircraft fuselages will be carried out. The analysis will include such factors as relative thicknesses of aviation profiles, geometric elongation of airfoils and fuselages, and slants of airfoils constituting the supporting surfaces of aircraft. The result will be the presentation of the most optimal parameters for passenger aircraft performing supersonic flights. The final aspect of the work will be the determination of the analytical pole of the aircraft, including the phenomenon of air compressibility in its scope, thus enabling the reading of the aircraft's flight characteristics for Mach numbers greater than M = 0,4.

Market research conducted by Airbus [1] confirms data collected by the World Bank on the increase in the number of passengers transported, they also forecast an increase for 2018-2038. The projected increase in demand for new planes and air connections is particularly high for intra-US, People's Republic of China and European Union connections, but also for intercontinental connections. An exemplary wide-body aircraft flight from Frankfurt am Main in Germany to Orlando in the United States of America takes 7.5 hours. A supersonic plane could cover this route in less than 4 hours. The growing demand for intercontinental air connections is a market niche that could be filled by supersonic passenger planes, significantly reducing travel times between distant places.

In order to select the optimal parameters of the structure and components, and thus increase the performance and refine the design, design analyses will be carried out taking into account not only aerodynamic parameters, but also the geometry of the wing and the entire aircraft. Also available power units of a similar application will be analysed in order to select the most appropriate source of thrust for the airframe. An extremely important aspect is also the environment in which the airframe will move, and therefore the characteristics of changes in gas parameters and flow depending on the flight altitude and speed.

Due to the airplane's cruising altitude of 25 000 m, an estimate has to be made for many of the flight altitudes that the airplane will reach during its climb. The calculations were carried out for five different heights, assuming the air density prevailing there. A constant increase in the speed of the aircraft was also assumed, where for the two highest ceilings they reach supersonic values.

Analyses and design assumptions have been made, preliminary aerodynamic calculations should be carried out to select the dimensions of the airfoil, fuselage, and the entire structure. For instance, based on the information gathered during the analysis of existing supersonic passenger aircraft structures, the aerodynamic profiles of the maximum thickness in the shifted profile were collected. The maximum relative thickness of the selected profiles does not exceed, also 5%.

For the fuselage design, the Whitcomb area Rule was used. It is a design principle for supersonic airplanes to avoid the adverse effects of the connection of wings, especially triangular wings with the fuselage. In line with this rule, the hull should be designed so that there is no overlap of local overpressure areas. According to this rule "... the combination of a wing with a fuselage will have the least drag if the position of the wing along the plane sections, normal to the stream, has the same character as the rotation body with the least drag"

The analytical polar of an aircraft is the basis for calculating its performance. The supersonic analytical polar was carried out for the preliminary design of an aircraft as shown in the figure 1. The flow around an aircraft is complex and the mathematical models that describe the phenomena vary depending on how accurate the data the engineer has. Aerodynamic tests, both in tunnels and in free flight, are very expensive and time-consuming. Therefore, at the design stage, it is necessary to calculate the aerodynamic characteristics of the aircraft using

the design data. The computational methods used to determine the characteristics are methods based on theoretical and experimental studies of flows. These methods allow calculating the analytical polar of an aircraft with geometry similar to that used today in flying machines in the range of Mach numbers from zero to four.

The method described in article was used to calculate the supersonic analytical polar of the designed aircraft. When starting polar calculations, it is necessary to have data such as geometric characteristics of the aircraft and to have analytical polar characteristics that ignore the phenomenon of air compressibility. Such parameters were assumed during the preliminary design.

The paper presents a complete analysis of the issues associated with supersonic flights. The topics of passenger aircraft construction were discussed. Recognition of the existing structures of supersonic passenger aircraft as well as plans for future constructions of such an application was carried out. A specific number of passengers, range, and economy were assumed to be combined by the designed aircraft and on this basis, calculations were made. The key element of the work was the determination of estimated and then exact aerodynamic characteristics, ending with the determination of the analytical supersonic polar of the aircraft.

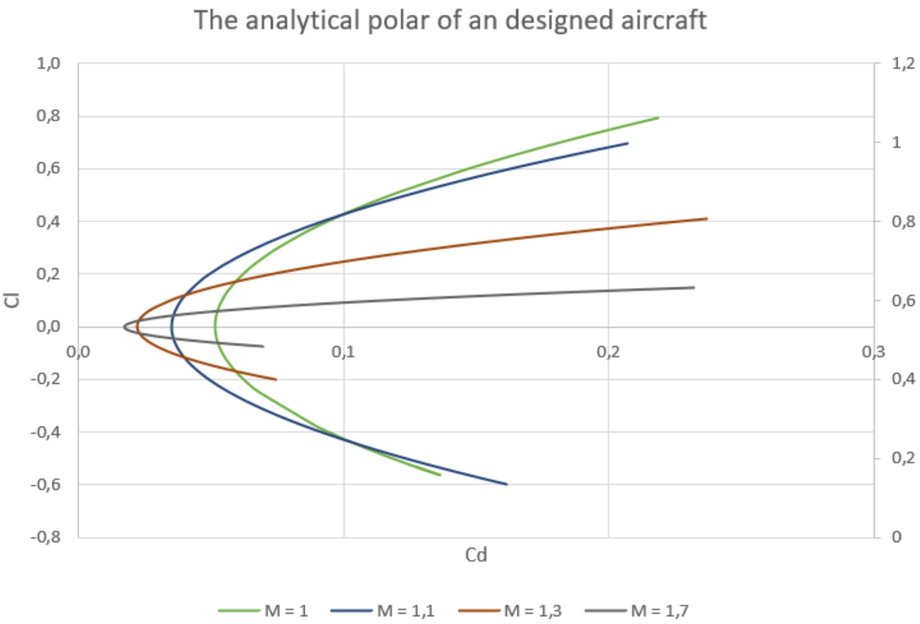

Figure 1 - The supersonic analytical polar of a designed aircraft

Keywords: Aircraft, Passenger, Supersonic, Preliminary Design

1. Introduction – Passenger Supersonic Aviation

Passenger aviation in the 20th century became the most efficient, fastest and safest means of transport on earth. Thanks to new technological advances, we can move from one end of the globe to the other in a time unattainable for other means of transport. While the designers of the largest design offices are competing to create ever larger, more reliable and more economical airliners, only one airliner in history has managed to survive on the market by breaking one barrier, the barrier of sound speed. In 1973, the British Aircraft Corporation, in cooperation with the French Aérospatiale, launched the Concorde aircraft into mass production. This plane reached an altitude and speed so far unheard of in civil aviation.

At an altitude of 18,290 meters, it reached a speed of 2,150 km / h, more than twice the speed of sound. Concorde's flight from London to New York took just over 3 hours. However, this plane was very uneconomical, it burned huge amounts of fuel, which made the ticket prices huge. Initially, it was not a problem because this plane perfectly fit into a market niche, offering fast flights to businessmen who were able to pay a high ticket price, despite the rising fuel prices, protests related to the nuisance of the sound thunder caused by the plane and the terrorist attacks of September 11, 2001, which significantly influenced the number of Concorde aeroplanes travelling had to be considered unprofitable and decommissioned. It happened in 2003, and commercial supersonic passenger flights have never been resumed since then.

Supersonic passenger planes can significantly reduce travel times, especially between continents, and thus change the face of modern public transport in the 21st century. In the face of the latest achievements in technology, material engineering, electronics and the use of computer design methods, the execution of such an aircraft now could turn out to be much cheaper and more efficient than during the Concorde design. In this paper, the problems related to the design and construction of such an aircraft will be discussed and a preliminary design of a supersonic passenger aircraft capable of taking at least 200 passengers on board and achieving at least twice the speed of sound will be performed.

The work will aim to create a preliminary design of a supersonic passenger plane. The scope of the work will include the analysis of the problems of supersonic flights, the selection of the aerodynamic system and aircraft equipment, the creation of preliminary aerodynamic calculations as well as the preparation of reference drawings of the aircraft

2. Problems in designing passenger supersonic airplanes

Thanks to the use of computer methods of design, flow analysis and material strength analysis, aviation technology has reached the stage where the parameters of the aircraft largely depend on the materials used for production, the methods of producing components and the length of the initial design phase. The time needed to design, test prototypes and implement them into mass production has decreased from even 11 years to 7 years in the Concorde era to 7 years in the case of the Airbus A350XWB, which was tested in 2013. Despite such advanced methods, several factors stand in the way, especially in the design of a supersonic aircraft. Without a thorough analysis of the phenomena occurring in supersonic flights and developing methods of avoiding them and optimizing the airframe characteristics for flights at speeds exceeding the speed of sound, it would not be possible to create a durable, safe and relatively low-maintenance aircraft. Factors having a significant impact on the design and construction of a supersonic passenger plane will be discussed.

2.1 Sound barrier and wave drag [3]

It is a common belief that one of the major obstacles in achieving near-sonic and supersonic speeds by aircraft is the sharp increase in aircraft drag. The increase in drag is only one of several factors that significantly change the aerodynamics and flight characteristics of an aircraft above the speed of sound. The increase in drag itself is also accompanied by a change in the value and application of the lift of the aircraft, increased aerodynamic heating, and a reduction or complete loss of stability and even the effectiveness of the control surfaces.

The geometry of the profile and wing of the aircraft significantly influences the formation of wave resistance and the development of the wave crisis, and thus the effects. The mechanism of wave resistance is as follows. When flowing around an aviation profile with convex surfaces, the air stream is locally narrowed to the plane at the point of the maximum thickness of the profile. If the flow velocity is high enough, the stream reaches the local speed of sound at the point of maximum negative pressure. This happens at a speed corresponding to the Macros. Then, in the widening cross-section of the stream, the speed does not decrease but continues to increase, creating the entire flow, a supersonic flow. Behind the profile, however, there is higher pressure, equal to the ambient pressure. The stream, on the other hand, has a subsonic velocity equal to the flow velocity. The particles moving in the rear part of the profile must brake and the pressure must drop to the value of the ambient pressure. Smooth deceleration of the supersonic stream is impossible, unfortunately, this sweep must be violent. A surface perpendicular to the profile is created, on which the moving air stream suddenly decelerates and compresses. This surface is in front of a flat wave of compressed air and is called the shock wave. As the speed increases further, the area of supersonic velocity on the profile surfaces increases, the shock wave enlarges causing the wave resistance to increase further. After the shock wave is formed on the upper surface of the profile, it soon appears also on the lower surface, increasing the already large resistance. Additionally, as a result of a sudden pressure change, the boundary layer tears off and the resulting turbulences increase the shape resistance. The rapid process of increasing aerodynamic drag, which was an obstacle in the form of a "shield" made of condensed air, was called the "sound barrier" as early as 1936. There is a direct relationship between such geometric dependencies of the wing as its elongation, the skew angle and the relative thickness of the profile and the wave drag coefficient as a function of increasing Mach number.

It can be assumed that the total drag coefficient Cx in the speed range from Ma = 0.3 to Ma = MaCr is invariable (for a constant angle of attack) and is equal to the resistance value for the flow velocity Ma = 0.3. After the critical Mach number is exceeded, mechanical energy losses occur on the upper and lower surface of the wing as a result of the previously discussed shock waves, resulting from a rapid change in the flow parameters. The intensive increase in the frontal resistance caused by the occurrence of the wave resistance should be calculated from the dependence:

$$C_x = C_{xpr} + C_{x\,i} + C_{x\,f} \tag{1}$$

C_{xpr} – airfoil drag coefficient, C_{xi} – induced drag coefficient, C_{xf} – wave drag coefficient

For velocities corresponding to flow velocity Ma> 1, the wave drag coefficient can be calculated from the equation:

$$C_{x\,f} = \frac{4(\alpha^2 + \bar{g}^{\,2})}{\sqrt{Ma^2 - 1}} \tag{2}$$

α – angle of attack $\bar{g}$ – relative airfoil thickness

Changing the Mach number causes a change in the course of the characteristics of the wing. The value of the C_z max coefficient decreases as a result of the pressure decrease at the upper surface of the airfoil. As a result of the inclination of the curve towards higher Mach number values, it means a decrease in the perfection of the wing and a greater increase in the value of the total drag coefficient.

2.2 Thermal barrier

Due to the rapid increase in pressure caused by the slowing down of the stream, the braking temperature. It causes the body to heat up quickly. The temperature at the stagnation point is [2]:

$$T \quad = T_\infty\left(1 + \frac{Ma_\infty^2}{5}\right) \tag{3}$$

T_∞, Ma_∞ - temperature, Mach number of undisturbed flow

Other points on the surface of the profile are also subject to aerodynamic heating (Figure 2) as a result of pressure pile-up. Due to the different values of the slowing down of the stream, they are characterized by a lower braking temperature, the so-called reduced temperature [2].

$$T_r = T_\delta(1 + r\frac{k-l}{2}Ma_\delta^2) \tag{4}$$

T_δ, Ma_δ – temperature and Mach number at the boundary of the boundary layer, r – reduced temperature coefficient, k – isentropic adiabatic exponent, l – wingspan

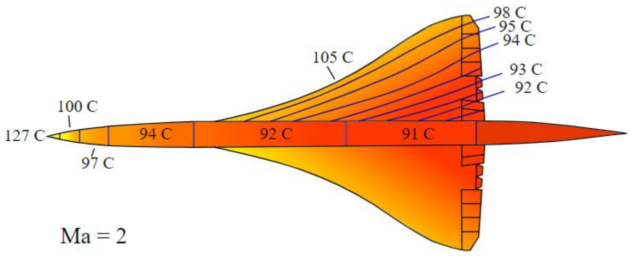

Figure 2 – Temperature of several Concorde aircraft components during the flight [8]

As a result of aerodynamic heating, the applicability of the current construction materials is very limited. Already at 100 degrees Celsius, the process of losing strength properties of aluminium begins, and at 370 ºC, titanium loses its properties. For the safety of the structure and, above all, passengers, an analysis of the airframe structure heating should be performed. Then, sensitive areas of the sheathing should be made of materials resistant to high temperatures. Unfortunately, this will increase the cost of building such an aircraft. However, it will significantly improve the performance and safety of passengers travelling on such a plane.

3. Requirements for preliminary designed aircraft

Before commencing the design assumptions phase, it is necessary to clearly define the parameters to which the designed structure is to pursue. This will have a direct impact on the analysed components, the selection of appropriate aerodynamic parameters and the materials considered for the application. For the designed supersonic passenger aircraft, the following parameters were adopted, which the design should be capable of achieving:

- Cruising speed at the level of Mach number equal to Ma = 2.6
- Cruising ceiling height equal to H_p = 25,000 m
- Aircraft weight not exceeding m_0 = 100,000 kg
- Maximum take-off weight not exceeding MTOW = 260,000 kg
- Total engine thrust at the sea level T_{sum} = 1 000 kN
- The range of the aircraft is at least L = 6,500 km
- At least 220 passengers taken on board

Apart from the purely technical parameters that the design should achieve, the practical parameters of the aircraft should be kept in mind. The structure must be relatively profitable, therefore it must take as many passengers as possible. You should also remember about production costs, an expensive plane will be harder to sell by a manufacturer even in the case of very good construction performance.

4. Preliminary design assumptions

In order to select the optimal parameters of the structure, components, and thus increase the performance and refine the design, design analyses will be carried out taking into account not only aerodynamic parameters but also the geometry of the wing and the entire aircraft.

To standardize the calculations of the parameters of the atmosphere and to enable the comparison of the performance of aeroplanes tested in different atmospheric conditions, a conventional calculation scheme called the International Standard Atmosphere was introduced.

4.1 Aircraft configuration

An important factor determining the aerodynamics of an aircraft, and especially its drag, is the aerodynamic system. A description of the aerodynamic systems that work best during flights at supersonic speeds will be presented, and then a preliminary assumption of the aerodynamic system of the designed supersonic passenger plane will be made.

- Classic layout (so-called conventional); an aeroplane with such an arrangement has a horizontal tail and a vertical tail behind the wing.
- System without a horizontal tail (so-called without justification); in an aeroplane with this arrangement, the stability and longitudinal control of the aeroplane are ensured by the wing (the wing control surfaces play the role of the elevator)
- Canard configuration, a system often used in hunting supersonic constructions due to its stall resistance and good manoeuvrability. The elevator in this arrangement is located in front of the wing.

The initial choice of the layout of the designed aircraft was a non-horizontal tail layout due to the lowest aerodynamic drag.

4.2 Airfoils presumption

The phenomena occurring during the achievement of very high speeds by aeroplanes forced engineers to develop new solutions. The increase in drag, deterioration of aerodynamic characteristics and stability of the aircraft initiated numerous scientific studies. As a result of theoretical and practical research, it has clearly shown that the use of airfoils of the smallest relative thickness improves the aerodynamic parameters during supersonic and supersonic flights. In modern aeroplanes with speeds oscillating around and exceeding the Mach number equal to M = 1, the following types of aeronautical profiles are used to improve performance.

- Laminar - the maximum thickness of such a profile is significantly shifted back compared to a non-laminar biconvex profile. The maximum relative thickness can be displaced by up to 70% of the mean aerodynamic chord. Such a structure significantly helps to maintain the laminar boundary layer in a very large part of the profile
- Symmetrical - these profiles are characterized by the lowest drag at high air speeds. The use of such profiles can be found in airplanes flying at sonic speeds and in the tail of a significant part of airplanes
- Wedge - having very little drag at high supersonic velocities and even in the lower range of hypersonic velocities
- Biconvex - they are characterized by good aerodynamic characteristics at high subsonic speeds
- Lens airfoils - with sharp-edged profiles used in wings of supersonic aircraft currently under construction.

4.3 Power unit selection

Power units are a key component of passenger airliners, must produce enough thrust to ensure the aircraft flies at a certain altitude, be reliable for safety reasons, and burn enough fuel to make the flight profitable for the carrier. At the turn of recent years, manufacturers of turbine jet engines have made incredible progress in extending the service life of the engines known to us, reducing their combustion and increasing their thrust at the same time [4]. The aircraft engines of existing supersonic passenger aircraft structures were analysed, together with two engines developed over the last 25 years for the needs of the military sector as shown in Table 1.

Table 1 - Comparison of parameters of power units used in supersonic aeroplanes

Engine	Olympus 593	RD-36	F-119	F-135
Manufacturer	Rollce-Royce/Snecma	Kolesov	Pratt & Whitney	Pratt & Whitney
Applied in	Concorde	Tu-144	F-22 Raptor	F-35 Lightning II
Mass	3 175 kg	3 900 kg	1 360 kg	1 701 kg
Diameter	1,212 m	1,486 m	1,143 m	1,090 m
Length	4,039 m	5,976 m	5,483 m	5,590 m
Maximum Thrust	169,2 kN	196,13 kN	156 kN	191 kN
Fuel consumption	$33{,}8\,\frac{g}{kN\times s}$	$35{,}5\,\frac{g}{kN\times s}$	$17{,}28\,\frac{g}{kN\times s}$	$25\,\frac{g}{kN\times s}$

The development of turbine jet engines clearly shows that it is possible to develop an engine that will provide sufficient thrust for such a machine while at the same time having relatively low fuel consumption. Due to the lack of a jet engine, developed in the last 10 years, that could be used as a power unit for the designed aircraft, it was assumed that the engine used in the designed structure would have the following parameters presented in Table 2.

Table 2 - Parameters of engine for predesigned aircraft

Mass	4 500 kg
Diameter	1,6 m
Length	7 m
Thrust without afterburner	285 kN
Thrust with afterburner	330 kN
Specific fuel consumption	$20\ \frac{g}{kN \times s}$
Specific fuel consumption (With afterburner)	$35\ \frac{g}{kN \times s}$

5. Aerodynamic calculations [5]

After preliminary analyses and design assumptions have been made, preliminary aerodynamic calculations should be made to select the dimensions of the airfoil, fuselage and the entire structure. The results will allow the calculation of the initial aerodynamic characteristics of the airframe, the estimation of its mass and the correct weight balance.

- Thrust load coefficient

$$\eta_T = \frac{m_0}{T} \tag{5}$$

Based on the analyzes, it was assumed: $\eta_T = 230\frac{kg}{m^2}$

- Preliminary mass of an aircraft

$$m_{start} = \eta_T * T \tag{6}$$

$$m_{start} = 262\ 200\ kg$$

- Lift surface load coefficient

$$p = \frac{m_0}{S} \tag{7}$$

Based on the analyzes, it was assumed: $p = 280\frac{kg}{m^2}$

- Lift surface area

$$S = \frac{m_{start}}{p} \tag{8}$$

$$S = 936\ m^2$$

- Aspect ratio

$$\lambda = 2{,}5$$

- Wingspan

$$l = \sqrt{\lambda \cdot S} \tag{9}$$

$$l = 48{,}38\ m$$

6. Components geometry

After making the initial aerodynamic calculations, you should start calculating the geometry of individual components.

The geometry and dimensions of the wing are shown in the figure below (Fig. 3)

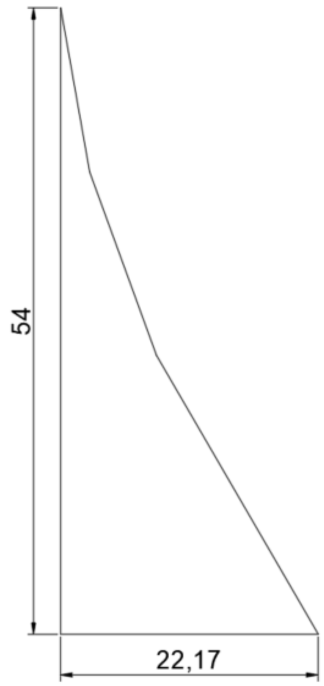

Figure 3 – Wing Geometry

The length of the fuselage was determined based on the statistical length of the fuselage of supersonic aeroplanes and existing supersonic passenger aeroplanes.

For the designed aircraft, the fuselage length was initially assumed to be:

$$l_k = 90\ m$$

This length may be changed due to the possible correction of the hull cross-sectional area, in order to keep the transonic area rule.

The transonic area rule is a design principle for supersonic aeroplanes to avoid the adverse effects of the connection of wings, especially triangular wings, with the fuselage. According to this rule, the fuselage should be designed so that there is no overlap of local overpressure areas. In practice, this means that the area of the fuselage cross-sections in the place where the wing is attached should be reduced by the value of the wing cross-section area corresponding to the given fuselage section. For strength reasons, this is not always possible. However, the fuselage cross-section at the point where the wing is attached should be reduced if possible as shown in Figure 4.

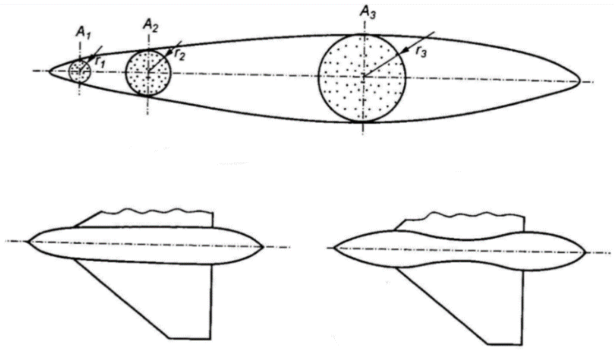

Figure 4 – Presentations of aircraft fuselage design with and without the transonic area rule

7. Calculating the wave drag [7]

The analytically calculated characteristics of an aircraft is the basis for calculating its performance. The flow around an aircraft is complex and the mathematical models that describe the phenomena vary depending on how accurate the data the engineer has. Aerodynamic tests, both in tunnels and in free flight, are very expensive and time-consuming. Therefore, at the design stage, it is necessary to calculate the aerodynamic characteristics of the aircraft using the design data. The computational methods used to determine the characteristics are methods based on theoretical and experimental studies of flows. These methods allow calculating the characteristics of an aircraft with geometry similar to that used today in flying machines in the range of Mach numbers from zero to four.

The method described below was used to calculate the analytical polarity of the designed aircraft. When starting polar calculations, it is necessary to have data such as geometric characteristics of the aircraft and to have analytical polar characteristics that ignore the phenomenon of air compressibility.

The entire computational range of Mach numbers should be divided into three ranges for which we will apply a separate mathematical model that allows us to calculate the polar:

- Incompressible flow M <= 0.4
- Supercritical flow $C_z < C_{zCr}$
- Supersonic flow M> M_{Crmax}

In terms of incompressible flows, the airplane polar can be calculated from the formula:

$$C_x = C_{x0} + \frac{C_z^2}{\pi\ \lambda_{ef}}\,(1 + \delta) \tag{10}$$

In terms of supercritical flows, the aircraft polar can be determined from the following formula:

$$C_x = C_{x0} + \frac{C_z^2 kr}{\pi\ \lambda_{ef}}\,(1 + \delta) - \frac{C_z\ C_z kr}{\frac{\delta C_z}{\delta\alpha}} + \frac{C_z^2}{\frac{\delta C_z}{\delta\alpha}} \tag{11}$$

In the scope of supersonic flows, the polar equation is calculated from the dependence:

$$C_x = C_{x0} + \frac{C_z^2}{\frac{\delta C_z}{\delta\alpha}} \tag{12}$$

In order to calculate the polar it is necessary to know the following functions of the flight number Ma:

- $C_{x0} = f_1(M)$
- $C_z kr = f_2(M)$
- $\frac{\delta C_z}{\delta\alpha} = f_3(M)$

7.1 $C_{x0} = f_1(M)$

The following function can be calculated basing on the aircrafts drag equation [6]:

$$C_x = C_{x0s} + C_{x0k}\frac{S_k}{S} + C_{x0V}\frac{S_v}{S} + \sum_n C_{xi}\,\frac{S_i}{S} + \Delta C_x int \tag{13}$$

7.2 $C_{zkr} = f_2(M)$

The lift coefficient equation can be calculated basing on this approximation:

$$C_{z\,kr} = \left(\bar{c} + \cos\chi_{0,25}\right)^{0,5} M^{-1,5} \tag{14}$$

7.3 $\frac{\delta C_z}{\delta\alpha} = f_3(M)$

To plot the function, first of all, the knowledge of $\frac{\delta C_z}{\delta\alpha}$ in the incompressible range is needed. If a profile with known load-bearing characteristics is used for the wing, the influence of elongation and the angle of skew can be included in the following dependency:

$$\left(\frac{\delta C_z}{\delta\alpha}\right)_{nieść} = \left(\frac{\delta C_z}{\delta\alpha}\right)_{prof}\left[1 + \left(\frac{\delta C_z}{\delta\alpha}\right)_{prof}\frac{1+\tau}{\pi\lambda_{ef}}\right]^{-1} \cos^2\frac{\chi_{0,25}}{2} \tag{15}$$

The calculations for the subsonic and supersonic ranges were divided by the narrow range of applicability of the Prandtl-Glauert formula. For the subsonic range, the relationship can be determined from the formula:

$$\frac{\delta C_z}{\delta\alpha} = \left(\frac{\delta C_z}{\delta\alpha}\right)_{nieść}(1 + 0{,}27M^2) \tag{16}$$

On the other hand, in the range of supersonic velocities, the function was calculated from the formula:

$$\frac{\delta C_z}{\delta\alpha} = \frac{3{,}8}{\sqrt{M^2-1}}\left(1 + \frac{S_{str}}{S}\right) \tag{17}$$

By making the calculations, the following characteristics for predesigned aircraft were obtained for the ranges of subsonic and supersonic Mach numbers as shown in figure 5.

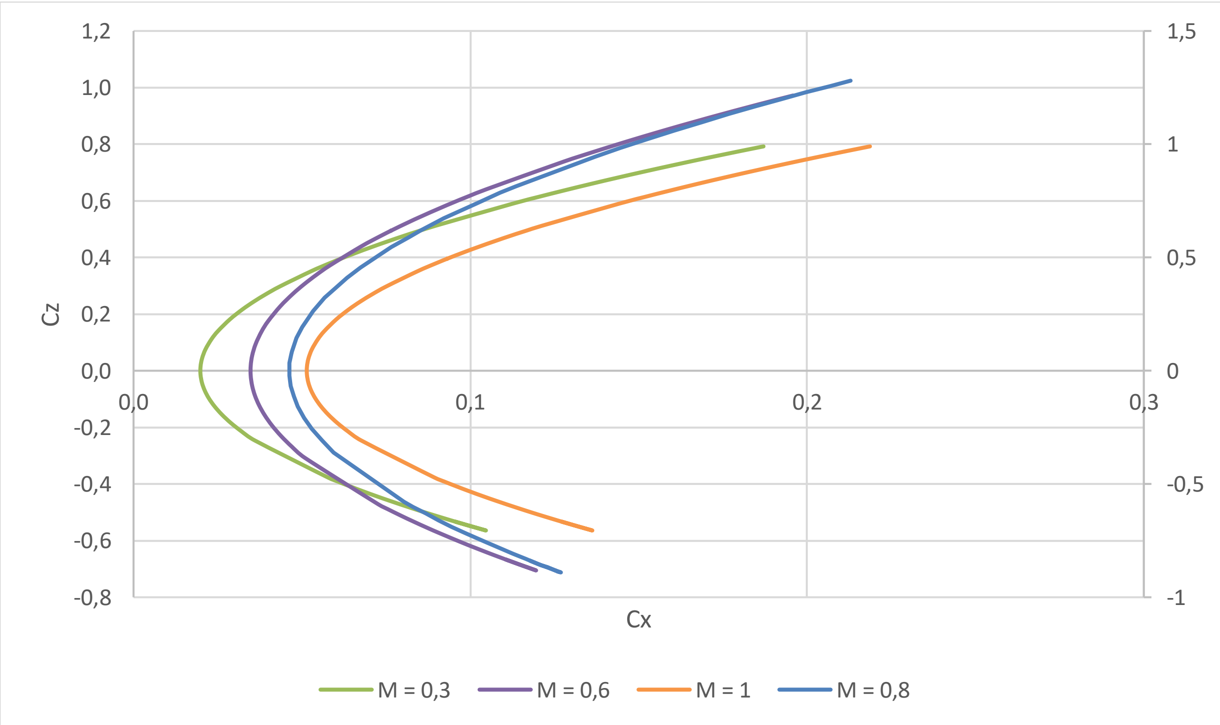

Figure 5 – Aircraft characteristics at subsonic and supersonic Mach numbers

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