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Experimental Study of Air-Assisted Rocket System Models for Launching Payloads into a Low Earth Orbit

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Abstract. This paper presents the results of aerodynamic testing of air-launch rocket kit models for launching payloads into a low Earth orbit. The work was performed in a low-speed wind tunnel at the Military University of Technology (MUT, Warsaw, Poland)), using symmetrical airflow. Two carrier aircraft models were tested, i.e., Su-22 and MiG-29 aircraft without launched payloads and with these payloads at a dynamic pressure of q = 500 [Pa] and the range of angles of attack at α = -28°÷28°. The values obtained related to the aerodynamic drag coefficient, aerodynamic lift coefficient, pitching moment coefficient and lift to drag ratio, and are given in tabular and graphic forms. The tests were primarily used to validate the numerical results obtained during implementation of the project "Air-assisted rocket system for launching payloads into low Earth orbit - feasibility study".
Keywords: mechanical engineering, aerodynamics, wind tunnel

1. INTRODUCTION

Since 2018, the Institute of Aviation Technology at the Faculty of Mechatronics, Armament and Aerospace of the Military University of Technology (MUT, Warsaw, Poland) has been implementing the research grant *"Air-assisted rocket system for launching payloads into a low Earth orbit - feasibility study"* with the purpose of demonstrating whether, under national conditions and with the support of national scientific, research and technological facilities, it is possible to design and build such a system. In the literature, these systems are classified as Responsive Space Assets, i.e., space object launching systems as opposed to traditional systems (nano- or micro-satellites), i.e., low-cost, reliable, accessible and mobile. In this context, such systems are understood as solutions that do not require any extensive or permanent ground-based infrastructure for space rocket launching and control, where a rocket-laden aircraft functions as a launch platform.

As part of the project implementation, versions of Su-22M4 and MiG-29A combat aircraft were selected as carrier-platforms with simulations and numerical analyses performed in accordance with a schedule, and the current test results are presented in [1-11]. The experimental tests were used to validate numerical models and perform numerical calculations of object characteristics for higher values of the *Ma* and *Re* numbers.

2. EXPERIMENTAL TESTS

The aerodynamic characteristics of MiG-29 and Su-22 aircraft models and space rockets were tested in a low-speed wind tunnel with a measuring space diameter of ∅ = 1.1 [m]. The models tested (scale 1:23) were created using 3D printing technology. The numerical representation of the aircraft and the systems necessary for 3D printing were developed using a commercial NX package on the basis of the proprietary measurements (aircraft) and source data (rockets). The aircraft geometric data was obtained using the "reverse engineering" method, by means of a 3D scanner to map the body of actual aircraft. Aircraft model tests were performed in set-ups without displaced control elements, with retracted landing gear, without supplies and with attached payloads to be launched. For Su-22 aircraft (Photo 1), tests were performed with an ALASA rocket attached to the wing [10], and for MiG-29 aircraft (Photo 2), with a W755[1] [10] rocket placed on the aircraft back. The tested models were made on a scale of 1:23.

[1]ALASA (American) and W775 (Russian) rockets to carry micro-satellites were examined in alternative space programmes.

The tests were performed at a dynamic pressure of q = 500 [Pa], which corresponded to the air stream speed in the tunnel at $v \approx 30$ [m/s]. During the tests, the Reynolds number was $Re_{Su\text{-}22}$ = 360000 and $Re_{Mig\text{-}29}$ = 295000, respectively.

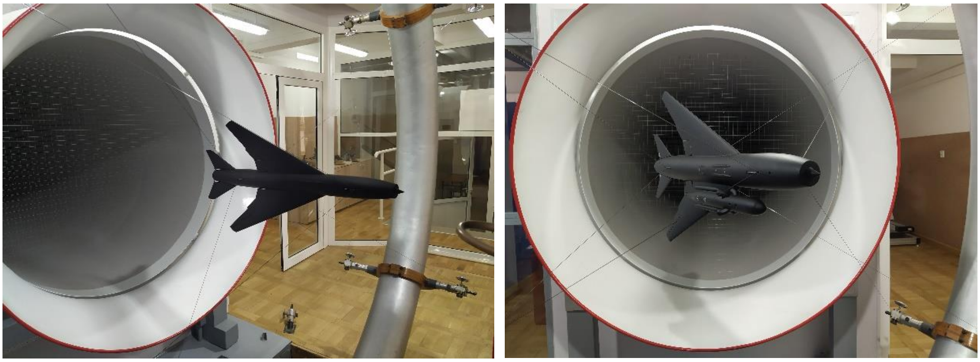

Photo 1. Su-22 aircraft model during tests in a wind tunnel in a set-up without a stored rocket and with an ALASA rocket stored

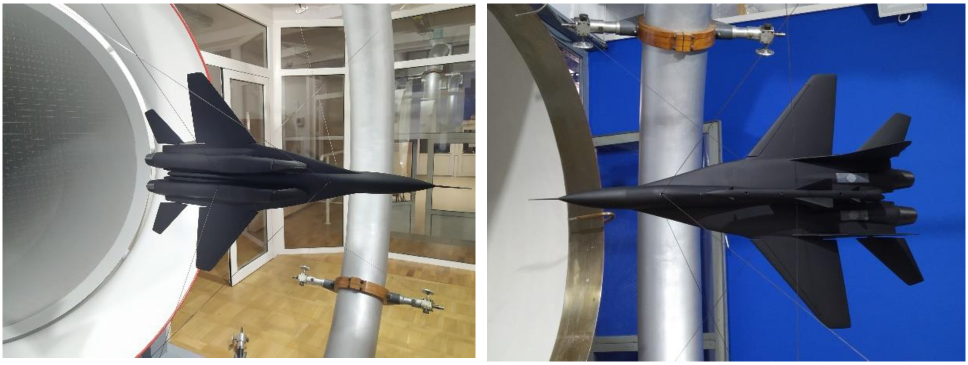

Photo 2. MiG-29 aircraft model during tests in the wind tunnel, with and without a rocket placed on the back

See Fig. 1 for the wind tunnel measurement system diagram. The methodology and the programme of aerodynamic characteristic calculation were developed on the basis of [12] and [13]. The tests were performed in the range of angles of attack $\alpha \pm 28°$, every 2°. Measurements were performed at the velocity pressure of q = 500 [Pa] (velocity $v \approx 30$ [m/s]). The coefficients were referenced to the aerofoil surface of aircraft models, i.e., $S_{Su\text{-}22}$ = 0.06929 [m^2], $S_{MiG\text{-}29}$= 0.0726 [m^2], and the pitching moment coefficient were additionally referenced to the average aerodynamic chord of the wings of the aircraft models, i.e., $b_{ASu\text{-}22}$ = 0.2015 [m] and $b_{AMiG\text{-}29}$ = 0.1653 [m].

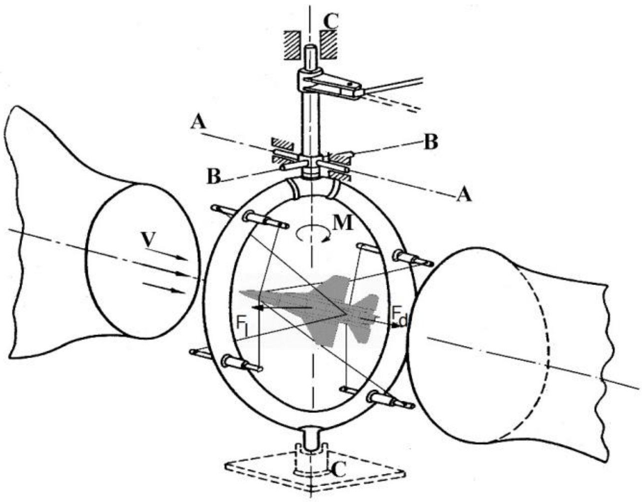

Fig. 1. Model suspension diagram in wind tunnel measurement space

The lift coefficients and drag force coefficients were determined for the flow-related system, i.e., the Ox_a axis was parallel to the air flow direction and located in the velocity vector direction, the Oy_a axis perpendicular to Ox_a was directed towards the right wing, and Oz_a was perpendicular to the Ox_ay_a plane. The aircraft models were suspended in the wind tunnel, so that the axis of aerodynamic balance moments crossed the point corresponding to the aircraft's centre of mass, and the aircraft's longitudinal axis coincided with the axis of drag of the aerodynamic weight. For the Su-22 carrier model, this distance was $x_{Qśr.m\ mod.}$ = 0.368 [m] from the beginning of the model, and in the case of the MiG-29 carrier model it was $x_{Qśr.m\ mod.}$ = 0.456 [m] from the beginning of the Prandtl tube. The strain gauges used in the measurement system made it possible to obtain results with an accuracy of ±0.01 [N] and ±1 [Pa] from the pressure transducer. Due to the finite diameter of the stream in the wind tunnel, the results were calculated on the basis of the methodology given in [13].

3. TEST RESULTS

The test results were presented in the form of graphs illustrating the curves of the basic aerodynamic characteristics:

- C_d=f(α) – drag coefficient as a function of the angle of attack;
- C_l=f(α) – lift coefficient as a function of the angle of attack;
- C_m=f(α) – pitching moment coefficient as a function of the angle of attack;
- C_m=f(C_l) – pitching moment coefficient as a function of the aerodynamic lift coefficient;

- K=f(α) – lift to drag ratio as a function of the angle of attack.

This related to the two tested models, in a smooth configuration and with payloads to be launched.

3.1. Su-22 carrier aircraft model tests

Drag coefficient C_d = f(α)

The C_d = f(α) for the Su-22 carrier aircraft demonstrated a typical parabolic shape (Fig.2). By analysing its course, it could be concluded that the suspended rocket had a significant impact on the characteristics only at low angle of attack values. At α = 0°, the rocket increased the C_d value by about 50% compared to the variant without stores. On the other hand, the values of maximum drag coefficients were similar, at α =-28° and α =28°.

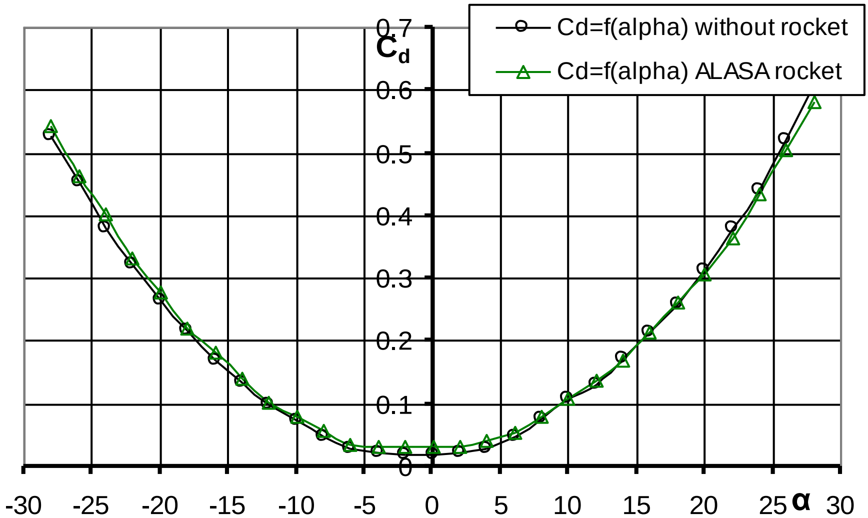

Fig. 2. C_d = f(α) characteristics of Su-22 aircraft model for the set-up with and without ALASA rocket

Table 1. Important numerical data

	Su-22 model without store	Su-22 model with store
α^o ($C_{d\ min}$)	-2	2
$C_{d\ min}$	0.02	0.03
C_d(α= -28^o)	0.53	0.54
C_d(α= 28^o)	0.61	0.58

Lift coefficient C_l = f(α)

The impact of the landing gear on the course of the aerodynamic lift coefficient characteristics for a smooth set-up and for a model with a store is shown in Fig. 3, while Table 2 presents other important data on these courses. The C_l = f(α) characteristic showed that the characteristics for the model with and without store overlap in the linear range. Differences in values increase together with the increase in the angle of attack, and for α = 28° rocket attachment caused a decrease in C_l value by about 4%.

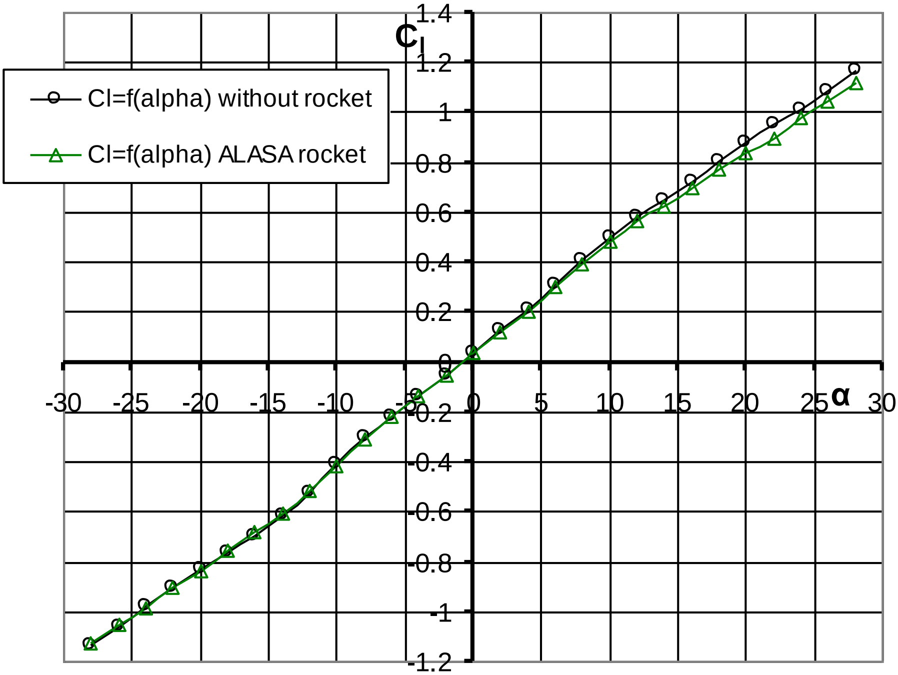

Fig. 3. C_l = f(α) characteristics of Su-22 aircraft model for the set-up with and without ALASA rocket

Table 2. Important numerical data

	Su-22 model without store	Su-22 model with store
α^o (C_l=0)	-1	-1
C_l (α=0)	0.04	0.035
$C_{l\ min}$	-1.13	-1.12
Cl_{max}	1.17	1.12

Pitching moment coefficient C_m= f(α) and C_m= f(C_l)

While analysing the C_m = f(α) (Fig. 4) and C_m = f(C_l) (Fig. 5) courses, it was clearly visible that all tested set-ups were characterised by static longitudinal stability, as $\partial C_m/\partial \alpha < 0$.

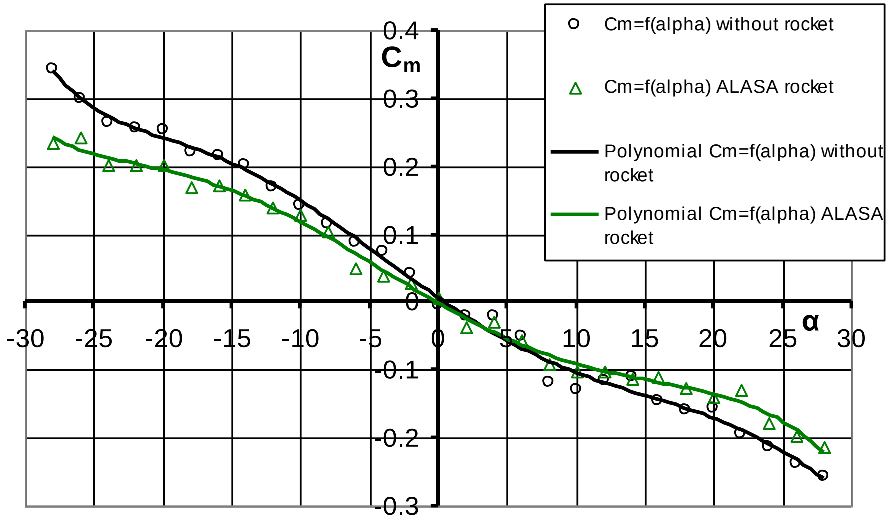

Fig. 4. C_m = f(α) characteristics of the Su-22 aircraft model in configuration with and without ALASA rocket

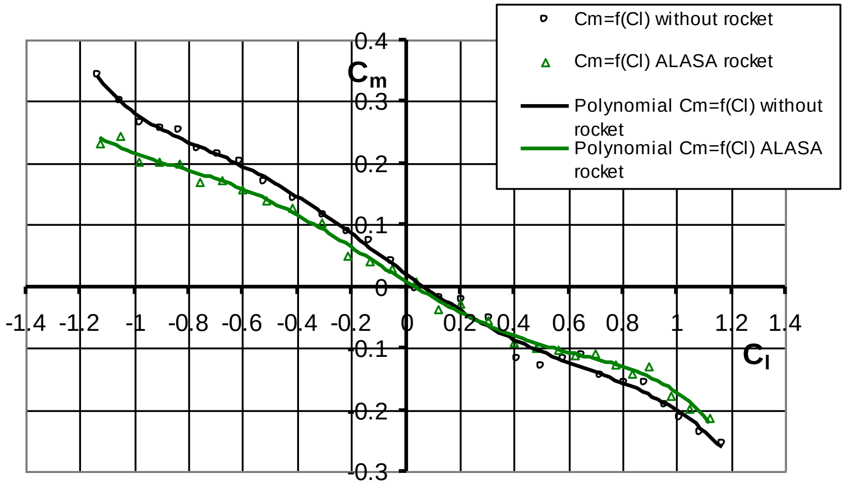

Fig. 5. C_m = f(C_l) characteristics of the Su-22 aircraft model in configuration with and without ALASA rocket

However, it should be added that the Su-22 carrier model with the ALASA rocket demonstrated lower stability than the model without storage (derivative $\partial C_m / \partial \alpha$ - the curve slope was smaller). By calculating the derivative [14]

$$\frac{\partial C_m}{\partial C_l} = \frac{x_Q}{b_A} - \frac{x_F}{b_A}$$

a stability reserve could be determined, which for the model without storage is 25%, while for the model with a stored ALASA rocket was 21%. Table 3 shows most important numerical data concerning this case.

Table 3. Important numerical data

	Su-22 model without store	Su-22 model with store
α^o (C_m = 0)	0	0
C_m (α=0)	0	0
C_l (C_m = 0)	0.04	0.03
$C_{m\ min}$	-0.26	-0.21
$\frac{\partial C_m}{\partial C_l}$	-0.25	-0.21

Lift to drag ratio *K* = f(α)

The course of the lift to drag ratio as a function of the angle of attack *K*=f(α) is shown in Fig. 6, while Table 4 contains the most significant numerical data.

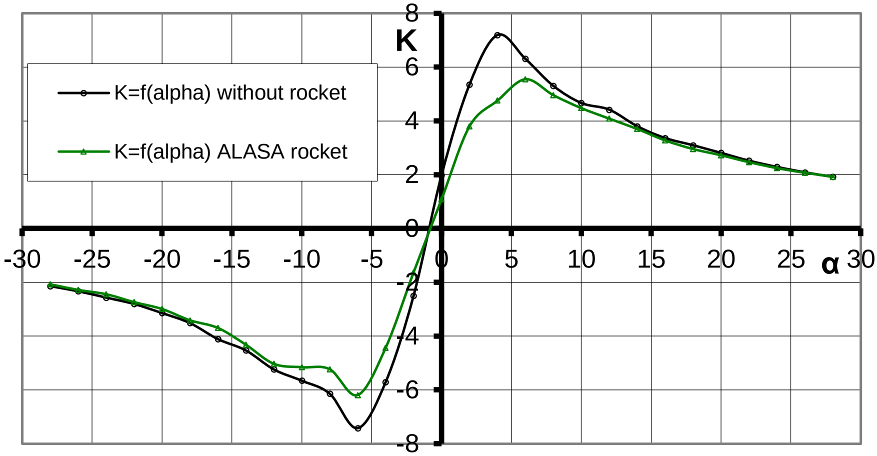

Fig. 6. *K* = f(α) characteristics of the Su-22 aircraft model in configuration with and without ALASA rocket

While analysing the course of the determined characteristics, the clear impact of the storage on the K = f(α) characteristic was visible. Storing of the rocket resulted in a decrease in the value of maximum lift to drag ratio, i.e., K_{max}, by about 23%. In addition, it could be seen that, after attaching the ALASA rocket, the optimum angle of attack was shifted from α = 4° to α = 6°.

Table 4. Important numerical data

	Su-22 model without store	Su-22 model with store
$-\alpha_{opt}{}^{o}$	-6	-6
K_{min}	-7.42	-6.19
$\alpha_{opt}{}^{o}$	4	6
K_{max}	7.19	5.54

3.2. MiG-29 carrier aircraft model tests

The second carrier aircraft model subjected to testing was the MiG-29. In the case of this carrier aircraft, a W755 rocket was to be mounted on its back. As before, 5 characteristics, i.e., C_d = f(α), C_l = f(α), C_m = f(α), C_m = f(C_l) and K = f(α) for a model with and without a rocket were determined.

Drag coefficient C_d = f(α)

The courses of the drag coefficient characteristics for the individual tested set-ups had a typical, parabolic form (Fig.7).

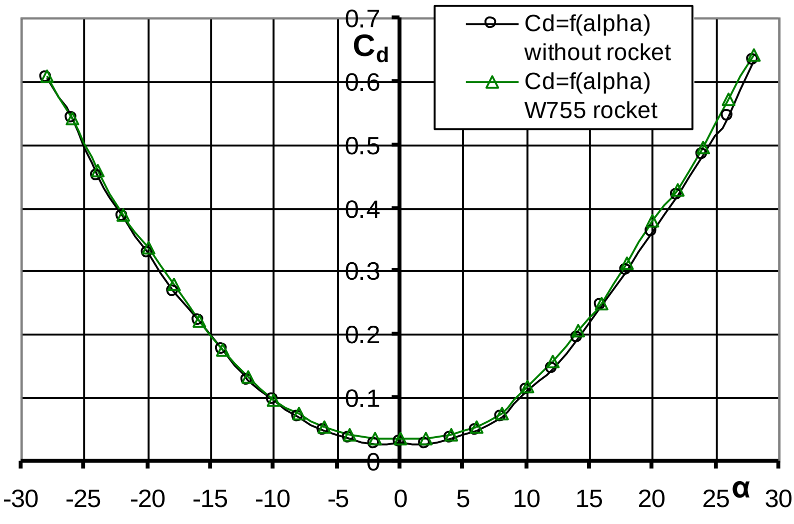

Fig. 7. C_d = f(α) characteristics of MiG-29 aircraft model for the set-up with and without W755 rocket

While analysing the characteristics of C_d = f(α) (Fig. 7), significant differences in the values obtained were observed only in the vicinity of the angle of attack α = 0°. For this angle, the drag coefficient of the aircraft model with the W755 rocket was C_d = 0.037. However, the aircraft model in the set-up without a rocket reached a value of C_d = 0.028. This resulted in an increase in the drag coefficient value by approx. 32%. However, at α=28°, the model with the rocket generated a drag coefficient greater only by approx. 2%.

Table 5. Important numerical data

	MiG-29 model without store	MiG-29 model with store
α^o ($C_{d\,min}$)	-2	-2
$C_{d\,min}$	0.028	0.037
$C_d(\alpha$= -28°)	0.61	0.61
$C_d(\alpha$= 28°)	0.63	0.64

Lift coefficient C_l = f(α)

Figure 8 shows the course of C_l = f(α) characteristics, and Table 6 shows the most important figures. The determined course was typical for this type of aircraft structure. No critical angle of attack was observed in the tested range of such angles. The characteristics practically overlap.

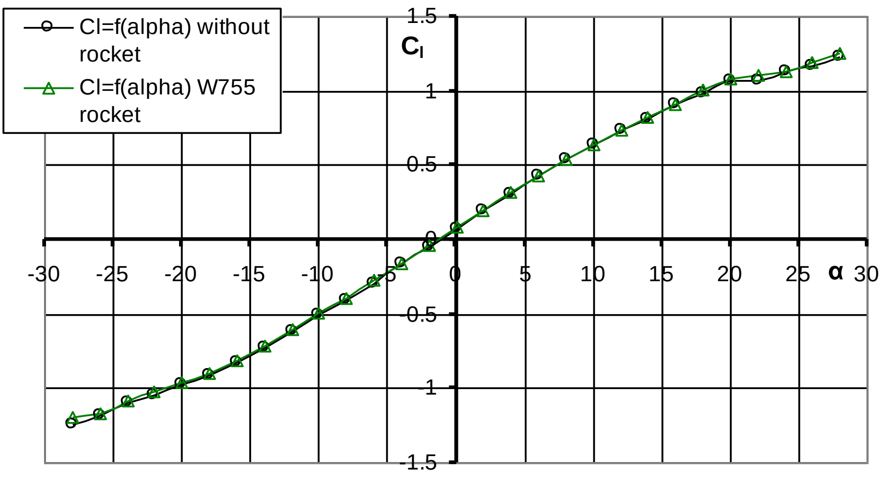

Fig. 8. C_l = f(α) characteristics of MiG-29 aircraft model for the set-up with and without W755 rocket

For the maximum value of the angle of attack, i.e., $C_{l\,max}$, values C_l = 1.23 for the model without a rocket and C_l = 1.25 for the model with the W755 rocket were obtained, respectively.

Table 6. Important numerical data

	MiG-29 model without store	MiG-29 model with store
α^o (C_l=0)	-1	-1
C_l (α=0)	0.07	0.09
$C_{l\,min}$	-1.24	-1.2
$C_{l\,max}$	1.23	1.25

Pitching moment coefficient $C_m = f(\alpha)$ and $C_m = f(C_l)$

While analysing the courses of $C_m = f(\alpha)$ (Fig. 9) and $C_m = f(C_l)$ (Fig.10), it was clearly visible that both tested set-ups were characterised by static longitudinal stability for the angle of attack $\alpha < 20^\circ$, as $\partial C_m/\partial \alpha < 0$. After exceeding the angle of attack of 20°, a loss of stability could be observed. Unlike the Su-22 aircraft model, in this case, all tested models were characterised by the same stability level (the $\partial C_m/\partial \alpha$ derivative had the same value - the inclination of the curves was almost identical).

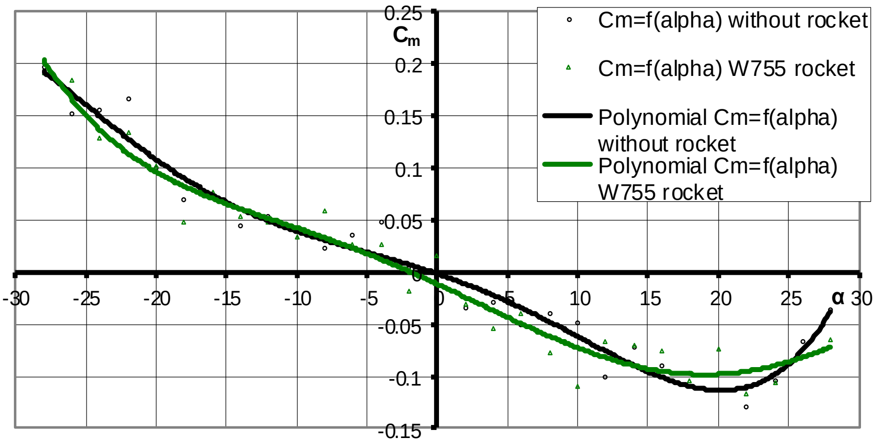

Fig. 9. $C_m = f(\alpha)$ characteristics of MiG-29 aircraft model for the set-up with and without W755 rocket

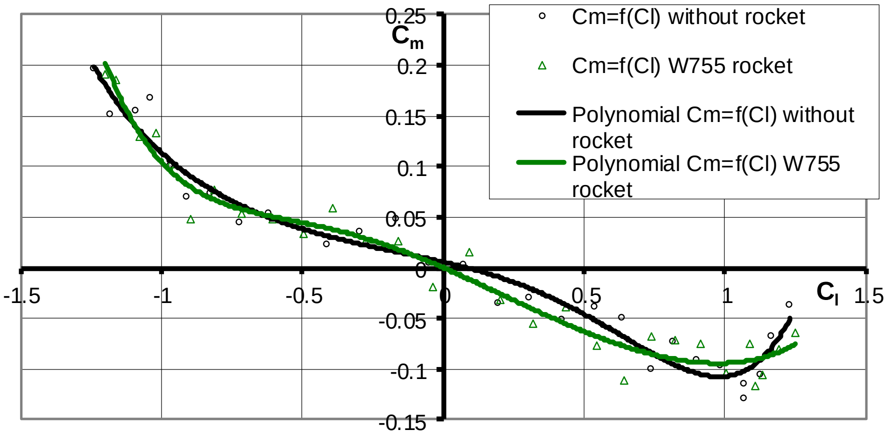

Fig. 10. $C_m = f(C_l)$ characteristics of MiG-29 aircraft model for the set-up with and without W755 rocket

Table 7. Important numerical data

	MiG-29 model without store	MiG-29 model with store
α^o (C_m=0)	1	0
C_m (α=0)	0.003	0.01
C_l (C_m = 0)	0.07	0.08
$C_{m\ min}$	-0.13	-0.11
$\frac{\partial C_m}{\partial C_l}$	-0.10	-0.10

Lift to drag ratio $K = f(\alpha)$

Figure 11 shows the $K = f(\alpha)$ characteristic for the MiG-29 aircraft model in a smooth set-up and with a W755 rocket, while Table 8 shows the most important figures. The $K = f(\alpha)$ characteristic showed that a model without store demonstrated a higher lift to drag ratio by approx. 12% (K_{max} = 9.01 obtained for the α=6° angle) than the model with a W755 rocket (K_{max} = 7.91 obtained for the α=6°) angle.

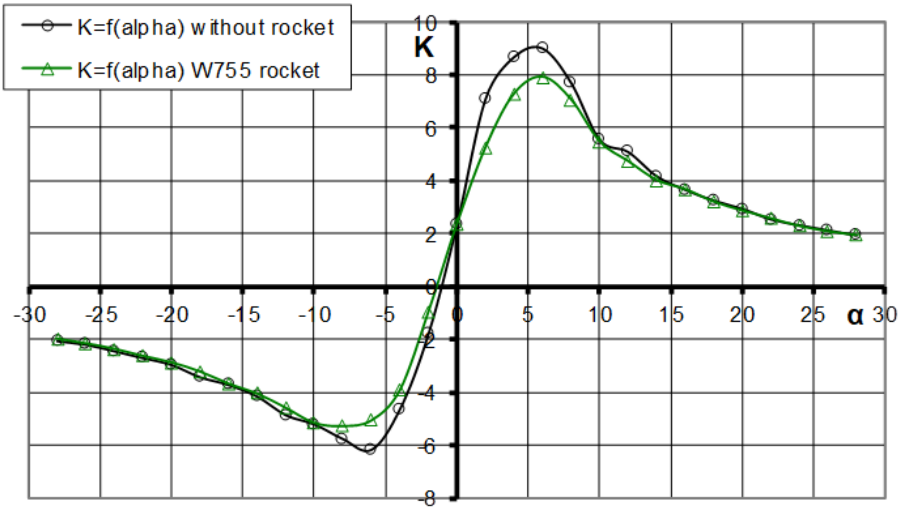

Fig. 11. K = f(α) characteristics of MiG-29 aircraft model in a set-up with and without W755 rocket

Table 8. Important numerical data

	MiG-29 model without store	MiG-29 model with store
$-\alpha_{opt}{}^{o}$	-6	-8
K_{min}	-6.14	-5.26
$\alpha_{opt}{}^{o}$	6	6
K_{max}	9.01	7.91

4. CONCLUSIONS

The main objective of the aerodynamic tests on aircraft carrier models launching payloads to the Earth low orbit was primarily to obtain the experimental data used to validate the numerical models. On the basis of the tests, a number of conclusions can also be drawn concerning the impact of attaching objects of this type to carrier aircraft. The tests on the aerodynamic characteristics of carrier aircraft models showed the impact on some of these characteristics. The model was tested in a wind tunnel, which due to the finite diameter of the air stream and the specified value of the ratio of the model wingspan to the L/D stream diameter in the tunnel required conversion of the results obtained in accordance with the algorithm presented in [13]. The results include coefficients for the different aircraft models. As a consequence, the Reynolds numbers in the model airflow and real object airflow deviate from each other.

The characteristics can also be calculated for higher Reynolds numbers using the methodology described in [15]. The results can also be used to validate the numerical results. A validated numerical model makes it possible to perform simulations for real objects.

Attaching the launched objects results in a significant increase in the drag coefficient C_d only in the range of angles of attack, α = -6°÷+6°. No impact by the attached objects on the aerodynamic lift coefficient characteristics C_l could be observed. A decrease in the lift to drag ratio value caused when the attaching the object launched could be observed, which for the Su-22 carrier aircraft model was approx. 23%, and for the MiG-29 carrier aircraft model was approx. 12%.

The research also showed that attaching a rocket under a Su-22 aircraft wing causes a decrease in the stability reserve, which is not observed when the launched object is attached to the MiG-29 carrier.

FUNDING

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Doświadczalne badania modeli lotniczo-rakietowych zestawów do wynoszenia ładunków na niską orbitę okołoziemską

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Streszczenie. W pracy przedstawiono wyniki doświadczalnych badań aerodynamicznych modeli lotniczo-rakietowych zestawów do wynoszenia ładunków na niską orbitę okołoziemską. Badania wykonano w tunelu aerodynamicznym małych prędkości WAT w opływie symetrycznym. Zbadano dwa modele nosicieli – Su-22 oraz MiG-29 bez wynoszonych ładunków oraz z wynoszonymi ładunkami przy ciśnieniu dynamicznym q = 500 [Pa] w zakresie kątów natarcia α = -28°÷28°. Uzyskane wartości współczynnika oporu aerodynamicznego, współczynnika siły nośnej, współczynnika momentu pochylającego oraz doskonałości aerodynamicznej przedstawiono w formie tabel i wykresów. Wykonane badania posłużyły przede wszystkim do walidacji wyników numerycznych, które były przeprowadzone w trakcie realizacji projektu „Lotniczo-rakietowy system wynoszenia ładunków na niską orbitę okołoziemską - studium realizowalności”.
Słowa kluczowe: inżynieria mechaniczna, aerodynamika, tunel aerodynamiczny