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LABORATORY TESTS OF THE AERODYNAMIC DRAG COEFFICIENT OF THE FLAG AS A BODY WITH LOW STIFFNESS

ANDRZEJ WILK AND MARIUSZ SKUTA

Institute of Power Engineering and Turbomachinery,
Silesian University of Technology,
Konarskiego 18, 44-100 Gliwice, Poland
awilk@imiue.polsl.pl

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Abstract: The shape and drag of bodies with small stiffness may change during the airflow. This problem refers to such bodies as flags, bands, banners, flapping sails as well as blades and cables which vibrate due to the flow.

Laboratory tests carried out to point out the aerodynamic drag coefficient of a flag are discussed in this article. The laboratory tests were carried out in an aerodynamic tunnel at different airflow velocities for flags with different dimensions made of fabrics of different roughness and stiffness. The drag coefficient value decreases with the increasing airflow velocity. The drag coefficient is higher for materials with higher roughness. The drag coefficient value is also influenced by the fabric stiffness and kind of edge.

Great engineering importance to the stability of a structure (*e.g.* a flag mast) and the safety of nearby persons and buildings are attached to the analysed problem.

Keywords: aerodynamic drag coefficient, flag

Notation

c_x – aerodynamic drag coefficient [–]
D – measuring channel diameter [m]
F – characteristic surface of the body [m^2]
F_1 – measuring channel surface area [m^2]
h – flag height [m]
l – flag length [m]
Q – volumetric flow rate [m^3/s]
R – reduced drag [N]
R_P – flag and hoop drag [N]
R_O – hoop drag [N]
R_x – aerodynamic drag [N]

v – undisturbed flow velocity [m/s]
ρ – fluid density [kg/m^3]

1. Introduction

There are forces that react to the body being under the flow of a fluid. The fluid reaction force on a solid body is the total of the resultant tangent forces inducted by viscosity and pressure forces, *i.e.* the forces normally reacting to particular elements of the body surface. The resultant force acting the undisturbed flow direction is the so called aerodynamic (hydrodynamic) drag and the resultant force perpendicular to the undisturbed flow direction is the so called lift.

It appears from the practice as well as from a dimensional analysis that the aerodynamic drag is proportional to the fluid density, the fluid velocity square and depends on the body dimensions [1]. That is why the formula for an aerodynamic drag is traditionally given as:

$$R_x = c_x \cdot \frac{\rho \cdot v^2}{2} \cdot F. \tag{1}$$

The proportional coefficient c_x depends on many factors connected with both the flow (especially the Re number) and the body (shape, kind of surface) [2].

The aerodynamic drag consists of two basic components:

1. the profile drag resulting from the heterogeneous field of pressure around the body,
2. the surface friction drag.

It is possible to determine the aerodynamic drag coefficient by measuring the real subjects or their models by testing (in aerodynamic tunnels). It is difficult to determine the profile drag or the friction drag alone because the body's shape and its surface structure are inseparable.

The profile drag is determined in tests for models in scale [3]. The surface structure modelling is difficult in such conditions [4]. The same remarks refer to determining the drag coefficients using numerical methods. In order to simplify the problem, laboratory tests or numerical calculations are carried out on smooth bodies and the results are corrected afterwards [5].

It is a much more complex problem to determine the drag coefficient for bodies with small stiffness. Due to the body's small stiffness its shape may change as a consequence of the pressure field reaction on the body.

This problem refers to bodies made of materials with small stiffness (higher and less predictable changes of shape – flags, bands, banners, flapping sails) and elements of structures vibrating due to the flow (blades, cables) [6]. In such cases numerical modelling is more difficult because of numerical mesh changes during calculations and due to the fact that the boundary layer must be modelled for bodies with roughness [7–9].

The laboratory tests carried out to determine the aerodynamic drag coefficient of the flag are discussed in the article. It is an example of a body with a low stiffness and a rough surface, whose shape may significantly change in reaction to the fluid flowing around (flag flapping).

2. Test stand

The flag aerodynamic drag tests were carried out in an aerodynamic tunnel in the Fluid Mechanics Laboratory of the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology.

This tunnel is closed and consists of a fan, a pipe with two elbows, a confusor, a measuring space and a diffuser. The fan which forces the airflow in the tunnel is driven by a 4-gear electric motor. It makes it possible to conduct tests at four different flow velocities. The average velocity values in the measuring space are shown in Table 1.

Table 1. Undisturbed speed v values in the measuring space at different motor gears

Gear	v [m/s]
1	4.27
2	8.39
3	10.39
4	13.35

The tunnel measuring space diameter was $D = 0.290\,\mathrm{m}$. A hoop was installed in the measuring space. The tested flags were fastened to a tread fixed to the hoop vertically along its diameter. The hoop was fixed to a lever. The lever transferred the air drag acting on the flag on the balance. The electronic balance accuracy used in the tests was $\delta R = 0.1\ G = 0.981 \cdot 10^{-3}\,\mathrm{N}$. Due to the drag instability and a high sensibility of the balance, the measurement results were averaged.

3. Course of tests

Laboratory tests were carried out in an aerodynamic tunnel at different airflow velocities.

Forty two different flags were tested. Their fabrics and kind of edge ending are marked by letters A to G. Table 2 contains a list of flags used in the test. An overview of the selected flags is shown in Figures 1 and 2.

Table 2. A list of flags used in the test

flag symbol	A	B	C	D	E	F	G
fabric	artificial fabric (satin)	artificial fabric (satin)	cotton	double-thick cotton	polyester with vertical weaves arrangement	polyester with horizontal weaves arrangement	cotton (terry)
surface roughness	smooth	smooth	rough	rough	smooth	smooth	very rough
stiffness	flexible	medium stiff	medium stiff	stiff	very flexible	very flexible	stiff
edge finishing	hemmed edge	edge rolled up and sewed	cut edge	hemmed edge	hemmed edge	cut edge	cut edge

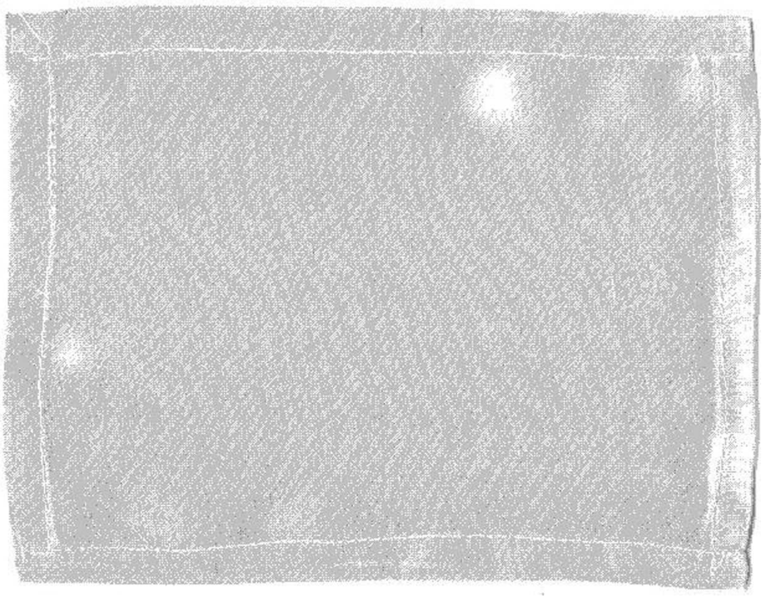

Figure 1. View of flag "B" (satin, rolled up and sewed edge)

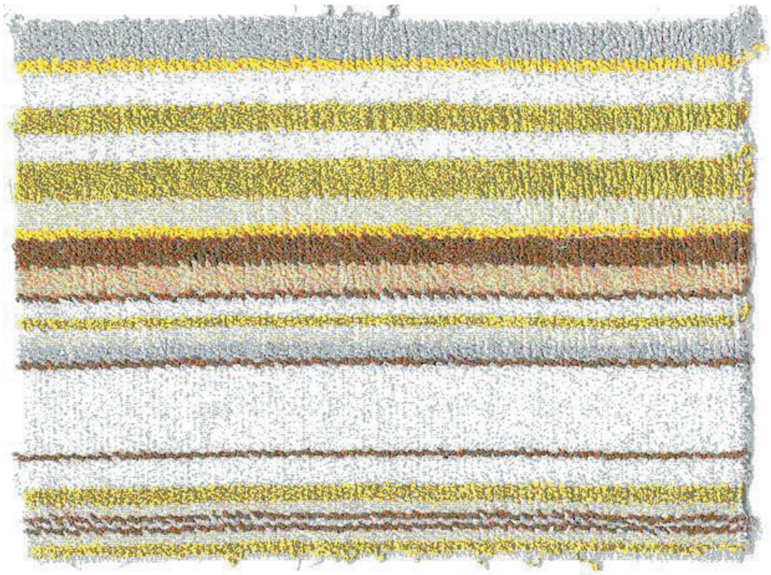

Figure 2. View of flag "G" (cotton – terry, cut edge)

The tests were carried out using flags made of the following materials:

- artificial fabric – satin (smooth surface) flags A and B,
- cotton fabric (rough surface) – flags C and D,
- cotton fabric – terry type (very rough surface) – flag G,
- polyester fabric (smooth surface) – flags E and F.

There are no methods for measuring the roughness of fabrics, therefore, the roughness was assessed only by comparing the fabrics one with another.

The edges of the flags were finished in different ways:

- cut edge (by scissors) – flags C, F and G,
- hemmed edge (by sewing machine) – flags A, D and E,
- edge rolled up and sewed (by sewing machine) – flag B.

Due to the fact that the flags were made of different materials and had edges finished in different ways, they had different ability of changing the shape. Such ability was conventionally named as "stiffness". There are no methods for measurements of stiffness for fabrics, so the stiffness was not measured. It was assumed that flags were:

- very flexible – flags E and F,
- flexible – flag A,
- medium stiff – flag B and C,
- stiff – flag D.

To change stiffness without changing roughness, two of the flags were made of the same fabrics but with one (flag C) or two layers (flag D).

The tests were carried out in 42 measurement series (Table 3). The series varied in terms of the fabrics of the flags and its dimensions – the height and the length.

Table 3. Measurement series

Flag dimensions $h \times l$ [cm × cm]	Flag symbol						
	A	B	C	D	E	F	G
	series symbol						
15 × 20	1	7	13	19	25	31	37
10 × 20	2	8	14	20	26	32	38
10 × 15	3	9	15	21	27	33	39
20 × 15	4	10	16	22	28	34	40
20 × 10	5	11	17	23	29	35	41
15 × 10	6	12	18	24	30	36	42

4. Calculation formulas

Analyses were conducted using the following formulas.

The measuring channel surface area:

$$F_1 = \frac{\pi \cdot D^2}{4}. \tag{2}$$

The undisturbed flow velocity:

$$v = \frac{Q}{F_1}. \tag{3}$$

The reduced drag was calculated as a difference between the drags for flags with a hoop and for the hoop only. It made it possible to determine the drag of the flag only:

$$R = R_P - R_O. \tag{4}$$

The drags values were measured on an electronic balance.

The main drag for the flag was a surface friction drag, hence the assumed characteristic surface was the friction surface, *e.g.* the flag surface:

$$F = 2 \cdot h \cdot l. \tag{5}$$

The aerodynamic drag coefficient was:

$$c_s = \frac{2 \cdot R^{\mathrm{RED}}}{\rho \cdot v^2 \cdot F}. \tag{6}$$

5. Tests results

The aerodynamic drag coefficient has been calculated according to the measurement results (6). The results are presented on diagrams as a relation between the drag coefficient and the undisturbed flow velocity. The diagrams (Figures from 3 to 8) are presented for each flag size.

The diagrams are presented below and the conclusions are presented in Section 6.

Figure 3 shows the dependence of the velocity on the aerodynamic drag for flags 10 cm high and 15 cm long, made of fabrics A to G (measurement series 3, 9, 15, 21, 27, 33, 39).

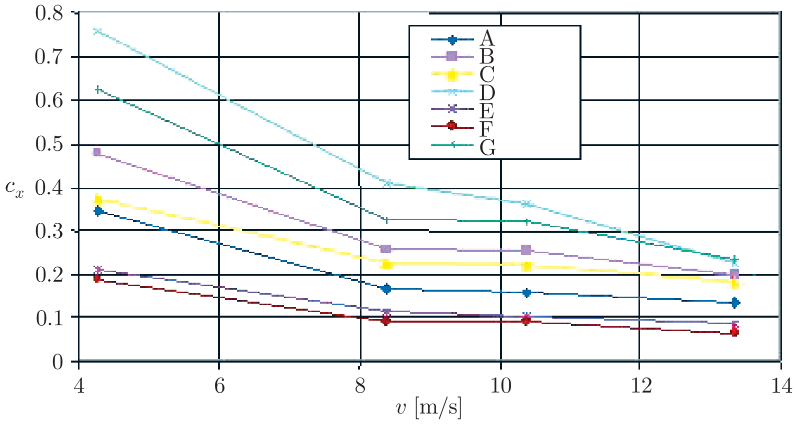

Figure 3. Relation of $c_x = f(v)$ for $h = 10\,\mathrm{cm} \times l = 15\,\mathrm{cm}$ flags

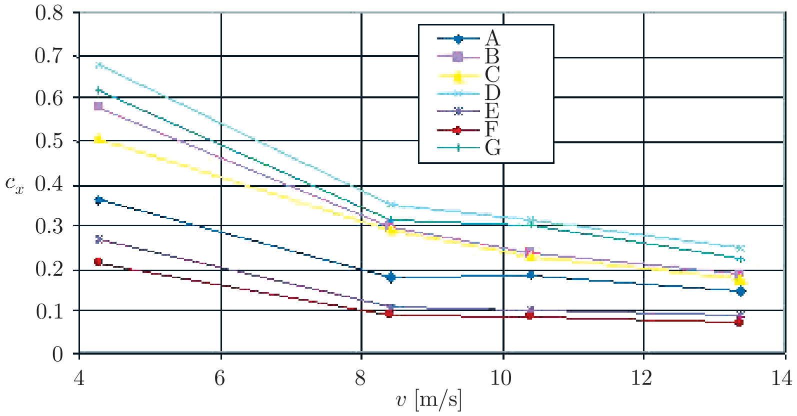

Figure 4. Relation of $c_x = f(v)$ for $h = 10\,\mathrm{cm} \times l = 20\,\mathrm{cm}$ flags

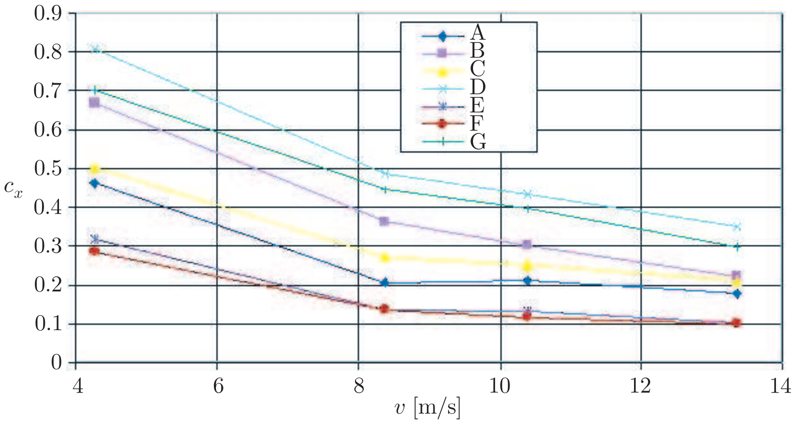

Figure 5. Relation of $c_x = f(v)$ for $h = 15\,\text{cm} \times l = 10\,\text{cm}$ flags

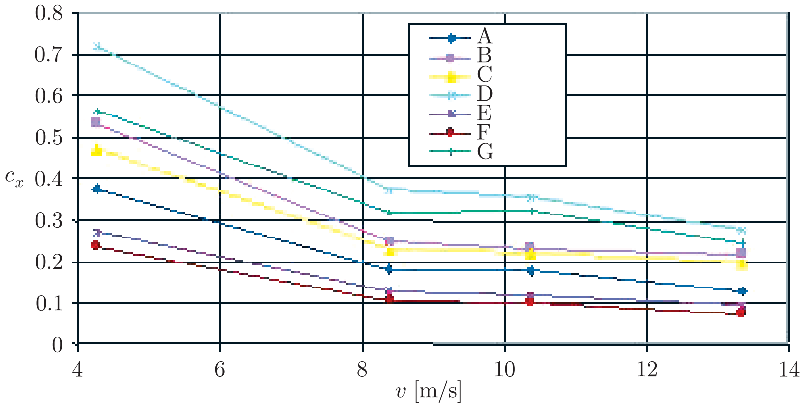

Figure 6. Relation of $c_x = f(v)$ for $h = 15\,\text{cm} \times l = 20\,\text{cm}$ flags

Figure 4 shows the dependence of the velocity on the aerodynamic drag for flags 10 cm high and 20 cm long, made of the fabrics A to G (measurement series 2, 8, 14, 20, 26, 32, 38).

Figure 5 shows the dependence of the velocity on the aerodynamic drag for flags 15 cm high and 10 cm long, made of the fabrics A to G (measurement series 6, 12, 18, 24, 30, 36, 42).

Figure 6 shows the dependence of the velocity on the aerodynamic drag for flags 15 cm high and 20 cm long, made of the fabrics A to G (measurement series 1, 7, 13, 19, 25, 31, 37).

Figure 7 shows the dependence of the velocity on the aerodynamic drag for flags 20 cm high and 10 long, made of the fabrics A to G (measurement series 5, 11, 17, 23, 29, 35, 41).

Figure 8 shows the dependence of the velocity on the aerodynamic drag for flags 20 cm high and 15 cm long, made of the fabrics A to G (measurement series 4, 10, 16, 22, 28, 34, 40).

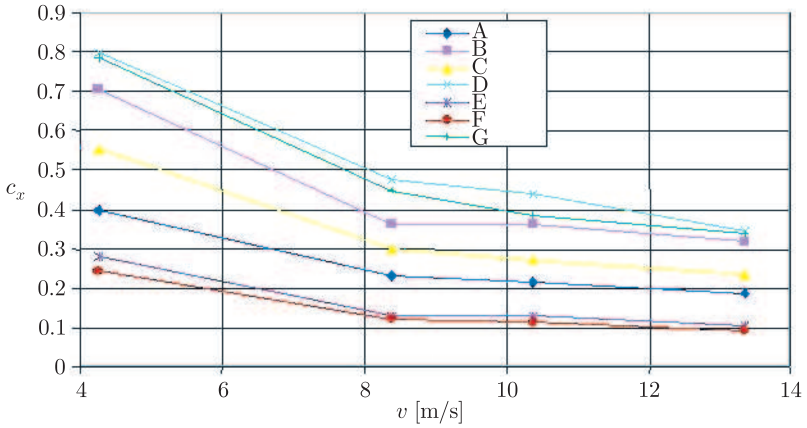

Figure 7. Relation of $c_x = f(v)$ for $h = 20\,\text{cm} \times l = 10\,\text{cm}$ flags

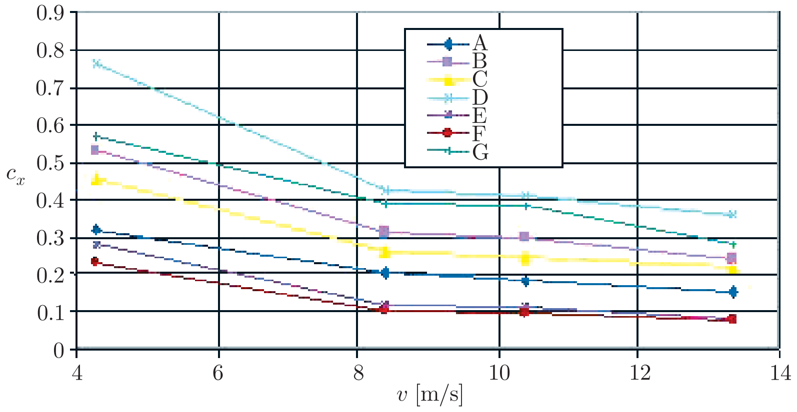

Figure 8. Relation of $c_x = f(v)$ for $h = 20\,\text{cm} \times l = 15\,\text{cm}$ flags

6. Test results analysis

Following the test results analysis it is possible to draw a conclusion that the drag coefficient for the flags depends on various factors.

A. In all cases, the value of the drag coefficient decreases with the increasing velocity (Figures 3–8). The biggest decrease is noticed for small velocities (in the range of $v = 4.27-8.39\,\text{m/s}$). the drag coefficient decrease is the smallest for velocities in the range of $v = 8.39-10.39\,\text{m/s}$.

The differences between the drag coefficients for different kinds of flags are the smallest for the highest velocity ($v = 13.35\,\text{m/s}$). It may be concluded that such attributes as the kind of material and the height to length relation do not have such a significant influence on the drag coefficient at a high velocity as at a small velocity.

B. The aerodynamic drag coefficient depends on the height to length relation of the flag. This relation can be noticed when the test results for flags with the same area are analysed (*cf.* Figures 3 and 5; Figures 4 and 7; Figures 6 and 9). The drag coefficient decreases slightly when the flag length increases.

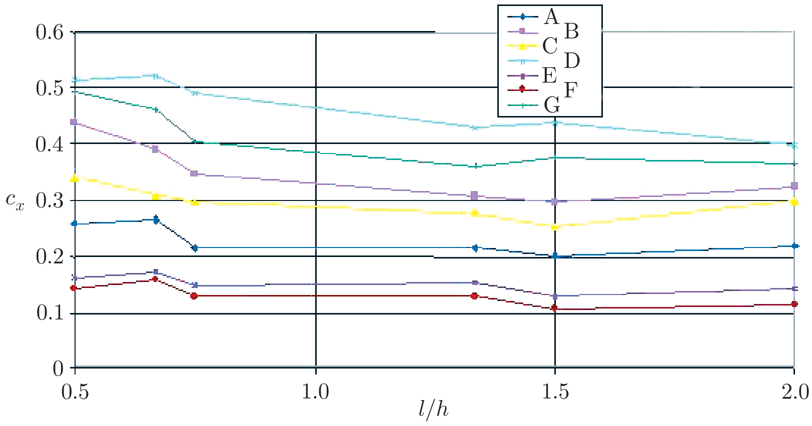

Figure 9. Relation of $c_x = f(l/h)$ for flags made of different fabrics

The flag's height to length relation influence on the drag coefficient is illustrated in Figure 9.

C. It can be noticed that the kind of the flag's material has a significant influence on the the drag coefficient value. The kind of the flag's material – the kind of fibre and weaving method have influence on the material roughness.

Fabrics made of natural materials (cotton) have a bigger quantity of fibres than artificial fibres and their roughness is higher. It is also the method of weaving that has influence on the roughness. It is cotton – terry that has the lowest and artificial fabrics that have the highest roughness.

The analysis shows that the drag coefficient is bigger ($c_x = 0.55-0.18$) for materials with higher roughness (fabrics C, D and G) and smaller ($c_x = 0.46-0.13$) for smooth materials (fabrics A, B, E and F). Flags made of polyester with a horizontal (parallel to the velocity direction) arrangement of weaves have the smallest drag coefficient values in all cases.

D. The stiffness influence. The stiffness was increased by double folding up the material. In all cases the biggest drag coefficient reached the double-thick flag. Also in case of other materials the drag coefficient was higher for flags with higher stiffness.

E. The flapping flag has a considerable influence on the drag coefficient. The frequency of flapping was not measured but observed only. The frequency of flapping was higher for longer flags. The coefficient was higher for flapping flags with a higher frequency drag.

7. Conclusions

The aerodynamic drag of a body with low stiffness whose shape may change due to the action of a fluid poses a complex problem. The drag coefficient depends on many factors connected with the shape of the body, the kind of the surface and also with the flow velocity.

An unambiguous conclusion drawn from the tests is that the drag coefficient value decreases when the flow velocity increases.

The drag coefficient decreases also when the height to length relation of the flag decreases.

It remains a separate problem to determine the influence of the flag's intensity (frequency) on the drag coefficient and the range of the body position change during the flapping. These problems need further tests and specifications.

Great engineering importance is attached to the analysed problem [10] because the forces acting on the flags during winds with a high velocity may have large values. A proper determination of these forces is fundamental for the stability of a structure (*e.g.* a flag mast) and the safety of nearby persons and buildings.

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