ICAS-96-7.3.4

USING THE FLUENT PROGRAM FOR OPTIMISATION OF THE FOWLER FLAP SYSTEM FOR THE ULTRA-LIGHT AEROPLANE

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Abstract

In this report, four modifications of a given Fowler flap system are presented. A basic airfoil was chosen and altered, and a flap was designed. The main objective was to design a high-lift flap while remaining a simple construction. The calculations were performed by using the Fluent V4 computer program. The Calculations were processed for different angles of attack and flap deflection angles. The calculation results were compared with data measured for this airfoil with flap in the Langley Research Centre. The final result is a satisfying flap shape and -position.

Symbols

FAR - Federal Aviation Regulation
GA(W) - General Aviation (Withcomb)
JAR-VLA - Joint Aviation Regulation - Very light Aircraft
LRC - Langley Research Centre, Virginia, USA
LS - Low Speed

F_y	N	Wall force in lift direction
Re	1	Reynolds number
V	m/s	Velocity of free stream
alpha,α	deg,rad	Angle of attack
c	m	Airfoil or airfoil - flap chord
c_l	1	Lift coefficient
delta,δ	deg	Angle of a flap deflection
x,y	m,1	Lift, drag directions
ρ	kg/m^3	Density of air
μ	kg/m/s	Dynamic viscosity

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Introduction

The design of the ultra-light aircraft OWL-1 (ULL - Sova P1) has begun in the Department of Aerospace Engineering of the Faculty of Mechanical Engineering, the Technical University of Brno, Czech Republic in 1994. It is a two-seat, whole metal, single wing aircraft based on the project of the light aircraft Zlín Z-80, designed for compliance with FAR 23.

A serious problem has been found at the beginning of that project. A minimum prescribed speed of 65 km/h (JAR-VLA) is necessary for the aeroplane, as well as a maximum weight of 450 kg. In order to obtain a sufficiently high lift coefficient, effective high-lift devices and a suitable airfoil were needed.

Another problem is, that the Faculty only has a very small table wind-tunnel which can not be used for the design of airfoils.

Both problems are addressed by using a given basic airfoil with Fowler flap and subsequently optimising this. For this, the NASA GA(W)-1 (LS(1)-0417) was chosen.

The airfoil data were taken from (2) and the flap co-ordinates were determined based on (3).

The next problem was the design of the Fowler flap. An airfoil that was easy to manufacture was looked for, because the OWL-1 has to be a cheap category aeroplane.

The flap system as given by (3) was changed. Therefore, new characteristics of the airfoil - flap system had to be determined. The Fluent program was chosen to get these characteristics.

Introduction to FLUENT V4

Fluent V4 is a computer program for modelling fluid flow, heat transfer, and chemical reaction processes.

By using Fluent, one can analyse quite quickly complex flow problems.

The size and scope of a problem (in terms of the number of computational nodes and the number of chemical species and reactions) is limited only by the available computer memory and the specific installation of Fluent.

Fluent V4 is a very useful program for a large area of science and production sphere.

The program models a wide range of phenomena by solving the conservation equations for mass, momentum, energy, and chemical species using a control volume based, finite difference method.

The equations are discrete on a curvilinear grid to enable computations in complex/ irregular geometry. A non staggered system is used for the storage of discrete velocities and pressures. Interpolation is accomplished via a first-order, Power-Law scheme or optionally via the higher order *QUICK* scheme. The equations are solved using the *SIMPLEC* algorithm with an iterative line-by-line matrix solver and multigrid acceleration or with the *GMRES* full field iterative solver.

More about the theoretical basis can be found in Chapter 13 of the Fluent V4 manual.

We can define the unique conditions that describe the problem via a wide variety of boundary conditions.

More about the boundary condition option is presented in Chapter 7 of the Fluent V4 manual.

Fluent V4 has two parts: The main program *Fluent* and the pre-processor *PreBFC*.

We can define the geometry and the structural grid in *PreBFC*. Solving is processed in the main program *Fluent*. Data is transferred to formatted or unformatted files.

See more about the program Fluent in (1).

Designing the airfoil - flap system

As mentioned before, the airfoil and Fowler flap co-ordinations were taken from (3).

The same flap co-ordinates were used for the calculation but the airfoil was modified.

It was cut at 90% of the chord, and four modifications were applied, designated TYP1, TYP2, TYP3 and TYP4.

Optimal airfoil - flap positions for the highest lift coefficient of the original airfoil are given in (3) but there the airfoil is designed to be cut at 92% to 98% of the main airfoil chord. The trailing edge part of such an airfoil is very thin. This causes some problems for the designer and constructor because they need very strong material to make that long edge.

Therefore, the airfoil was cut at 90% of the main airfoil chord and the hinge point of the Fowler flap was moved towards the front.

Those changes decreased the maximum lift coefficient but the trailing edge of the airfoil became thicker.

Presumptions and simplifications of the model and calculation

The flow around the airfoil - flap system was considered to be two-dimensional.

Eight calculations were performed. Table 1) gives the configurations for these calculations.

The models were built up of three parts.

The first part is the main airfoil. It is always in the same position of the calculation area, which is 6 units long in the left - right direction and 4 units high in up - down direction. One unit represents the basic GA(W)-1 airfoil chord. The main airfoil is then positioned between units 2 and 2.9 in the left - right direction and its thickness is truly proportional to its length. Vertically, it is situated in the middle of the calculation area. The shape of the airfoil was changed as it is shown in Appendix A.

The second part is the Fowler flap. Its positions for all cases are shown in Appendix A. The flap deflection is zero degrees or forty degrees and the flap rotates around hinge points P1, P2 or P3.

The co-ordinates of these hinge points are as follows:

P1: 95%,-4%
P2: 91%,-3%
P3: 91.5%,-3.5%

model	angle of attack	flap deflect.	hinge point position	Re *e6	comment
TYP1	0°	0°	P1	1.7	-
TYP1	7°	0°	P1	1.7	-
TYP1	0°	40°	P1	1.7	-
TYP1	7°	40°	P1	1.7	-
TYP2	0°	0°	P1	1.7	-
TYP2	7°	0°	P1	1.7	-
TYP2	0°	40°	P1	1.7	-
TYP2	7°	40°	P1	1.7	-
TYP3	0°	40°	P3	1.7	*
TYP3	7°	40°	P3	1.7	*
TYP4	0°	40°	P2	1.7	**
TYP4	7°	40°	P2	1.7	**

Table 1) Configurations of calculations

** Geometric model with flap neutral is the same as TYP2*

*** Geometric model with flap neutral is the same as TYP1*

The third part is the calculation area, or "tunnel". The model of the flow around the airfoil and the flap is limited to a rectangular area. The types of border conditions are presented in Table 2).

// Remark: *Pressure inlet* = there is an equal pressure on both sides of the calculation area border. //

// Remark: The boundary condition *Symmetry* was chosen for TYP3 for an angle of attack of zero degrees, but calculated data are similar as for pressure inlets. //

The geometry and the mesh were prepared in the *PreBFC*. Smoothing, recalculating for better mesh and checking the grid schemes were handled by procedures of the *PreBFC*.

Some examples of a mathematical and a physical grid are plotted in Appendix B.

model/α/δ	front side	upper side	back side	lower side
TYP1/0/0	velocity inlet 24.6 m/s	pressure inlet	pressure inlet	pressure inlet
TYP1/7/0	velocity inlet 24.4 m/s	pressure inlet	pressure inlet	velocity inlet 3 m/s
TYP1/0/40	velocity inlet 24.6 m/s	pressure inlet	pressure inlet	pressure inlet
TYP1/7/40	velocity inlet 24.4 m/s	pressure inlet	pressure inlet	velocity inlet 3 m/s
TYP2/0/0	velocity inlet 24.6 m/s	pressure inlet	pressure inlet	pressure inlet
TYP2/7/0	velocity inlet 24.4 m/s	pressure inlet	pressure inlet	velocity inlet 3 m/s
TYP2/0/40	velocity inlet 24.6 m/s	pressure inlet	pressure inlet	pressure inlet
TYP2/7/40	velocity inlet 24.4 m/s	pressure inlet	pressure inlet	velocity inlet 3 m/s
TYP3/0/40	velocity inlet 24.6 m/s	symmetry	pressure inlet	symmetry
TYP3/7/40	velocity inlet 24.4 m/s	pressure inlet	pressure inlet	velocity inlet 3 m/s
TYP4/0/40	velocity inlet 24.6 m/s	pressure inlet	pressure inlet	pressure inlet
TYP4/7/40	velocity inlet 24.4 m/s	pressure inlet	pressure inlet	velocity inlet 3 m/s

Table 2) Border conditions

Process of calculation

Calculations were conducted using the Fluent program. The Fluent V4.22 program was run on the Digital DEC station with 16 MB RAM. The optimum memory size required by the Fluent program is a bit higher, that is why the calculation consumed more time and some pictures, especially those with filled contours, could not be displayed and printed in full size. The maximum size of the grid was restricted to an amount of 15000 nodes.

// Remark: Therefore, TYP3 was calculated using the heavy-duty computer Silicon Graphics Power Challenge with more memory and with the Fluent V4.32 program. //

Preparing the model in the *PreBFC*

The following steps were carried out:

- The airfoil and the flap co-ordinates were typed as points,
- the curves were designed (type *Wall*) with respect to the mathematical grid,
- the "tunnel" was constructed (Type *Inlet*, or *Symmetry*),
- A manual grid was applied at complicated locations (for example, between the airfoil and the flap) where the automatically generated grid could diverge,
- the grid density around the airfoil and flap was changed,
- for the rest of the calculation area, an automatically generated grid was used,
- the grid was smoothed automatically by a *PreBFC* procedure and scanned locally for errors.

Model processing in the *Fluent* program

The *Fluent* program was used to continue the computation process as it is less memory - demanding than the *PreBFC*.

The model processing continued with the following actions:

- searching globally for errors in the grid,
- setting the boundary conditions for Inlets,
- choosing the computation methods:
  - a bigger step of iteration was set for the beginning of the calculation and afterwards, implicit Fluent values were applied,
  - the Reynolds stress model was switched on after reaching from 2000 up to 4000 iteration steps, depending on the speed of convergence. The Reynolds stress model is better for calculation of models with boundary layers,
- conducting the calculation to a time instant, where normalised residuals were lower than 1E-4.

Normalised residuals were calculated by dividing the increment of the quantity concerned (i.e. pressure, velocity, etc.) in one iteration by its total value.

Fast divergence occurred in some calculations. In those cases, the step of iteration or the number of calculation cycles for some quantities had to be changed until the process converged.

// Remark: the process was set up for a model with an angle of attack of zero degrees. For an angle of attack of seven degrees, several steps in the *PreBFC* could be skipped, thereby reducing the duration of the calculation process. //

Discussion and comparison of calculation and measured data

Results obtained by the Fluent program are presented in Table 3) and in Appendix C.

Equation (1) was used for calculating the lift coefficients from the wall forces which have already been determined before.

	Typ1	Typ2	Typ3	Typ4	Measure
c_l	alpha=0 deg , delta=0 deg				
	7°	0,3010	0,3010	0,2530	0,4200
	alpha=7 deg , delta=0 deg				
	0,9710	0,9830	0,9830	0,9710	1,1000
	alpha=0 deg , delta=40 deg				
	0,6480	0,8140	1,0420	1,4980	2,8800
	alpha=7 deg , delta=40 deg				
	1,7660	1,6360	2,1310	2,3650	3,4600

Table 3) Calculated and measured lift coefficients

We could not calculate the drag coefficients directly. The Fluent program gives incorrect wall forces in the *x* direction for models with a small relative thickness and higher angles of attack. It had to be done by special constructions but, at this stage, the drag was not so important for the computation process. All cases were calculated for Reynolds number of 1.7 million for the take-off and landing flights phase of the aircraft.

$$c_l = \frac{2 \times F_y}{\rho \times V^2 \times c} \qquad (1)$$

where F_y is for the wall force in the *y* direction (vertical to velocity), *c* represents the airfoil chord and equals unity because it is a one-unit model. The density is 1.225 kg/m^3 and the velocity results from the equality of the Reynolds numbers (equation (2)) of the model and the real aircraft.

$$Re = \frac{\rho \times V \times c}{\mu} \qquad (2)$$

where μ represents the dynamic viscosity, in the computation considered to be 17.75E-6 kg/m/s, and *V* is for the velocity of the real aircraft while landing or taking off and equals 25 m/s.

Differences between lift coefficients of the TYP3, TYP4 and types TYP1, TYP2 are obvious from the results. The results of the first two cases, TYP1 and TYP2, confirmed an incorrect design of the flap position. TYP3 is a little better and TYP4 is the best of all cases. The flap position in TYP4 is close to the expected optimum position of the flap for the OWL-1 aeroplane.

One can see that the lift coefficients depend more on the airfoil - flap position than on the shape of the gap between the airfoil and the flap.

An incorrect position of the flap can cause a significant loss of lift. This is very dangerous for the take-off and landing of the aeroplane. In TYP1 and TYP2, the lift coefficient had approximately the same values as for a plain flap. In this case, all advantages of the Fowler flap are lost.

Short comment on the calculation results

The data calculated for the neutral flap position are approximately the same as those measured in LRC. The C_l - alpha ratio is exactly the same.

The data for the flap deflected at an angle of forty degrees are different. It was supposed that the lift coefficient would be lower than the measured data for all cases, but the losses of lift of TYP1 and TYP2 were too high and the advantage of the Fowler flap was depreciated.

A big vortex can be observed at the back of the flap in both cases, and flow separation (stall) occurred on the whole upper surface of the flap.

The flow separation can be seen on the back part of the upper surface of the airfoil at an angle of attack of seven degrees.

The results of TYP3 range between types TYP1, TYP2 and type TYP4. The flow around the airfoil and the flap is not as smooth as in the case TYP4 and a quite large vortex is generated behind the flap. The flow separation moved from the trailing edges of the airfoil and the flap towards the front.

The results of TYP4 are better but it is not sure if they are sufficient for the aeroplane.

The flow around the airfoil and the flap is smooth and without any larger vortices in case TYP4.

Concluding remarks

The Fluent program can be used to get quite fast and cheap information about the lift and flow around the airfoil with the flap. But al those data are determined in a theoretical way and in order to verify what really happens, it is necessary to conduct measurements in the wind-tunnel or test flight.

The Fluent program is a powerful instrument for solving the problem of finding the optimum of the airfoil - flap position, i.e. for comparison purposes.

The time needed for preparation of any model for the calculation in the Fluent program is one of the biggest disadvantages of this system.

While calculating, it is useful to change only the boundary conditions for small angles of attack. For any greater angles of attack, it is better to make a new model and meshing each time, but this takes more time between calculations.

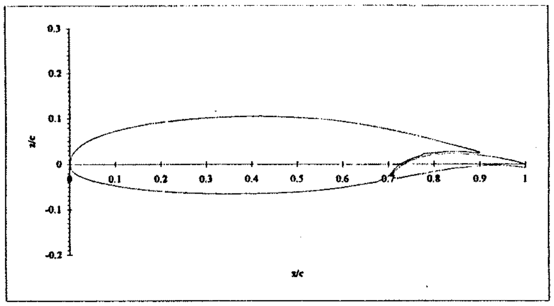
References

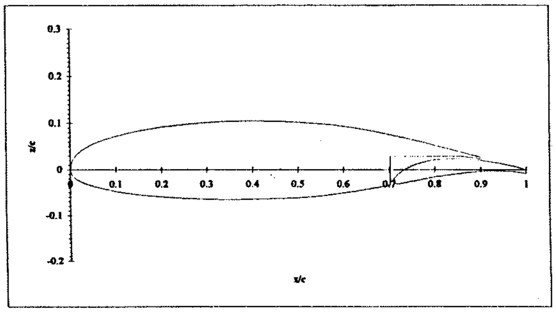
(1) Fluent Inc. - Fluent V4 Users Guide

(2) NASA TN D-7428, "Low-speed aerodynamics characteristics of a 17-percent-thick airfoil section for general aviation applications", R. J. McGhee and W. D. Beasley, 1973

(3) NASA CR-2443, "Development of a Fowler flap system for a high performance general aviation airfoil", W. H. Wentz jr. and H. C. Seetharam, 1974.

Appendix A

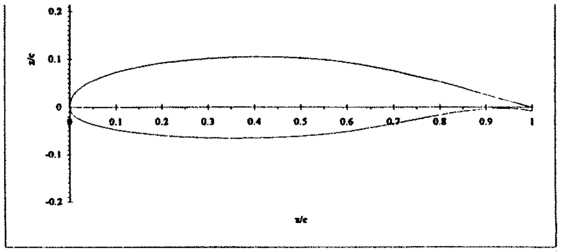




TYP1 and TYP4	
x/c	z/c
0.695	-0.03
0.7065	-0.02
0.713	-0.0115
0.7215	-0.003
0.736	0.005
0.753	0.0125
0.771	0.0185
0.778	0.023
0.808	0.025
0.828	0.0275
0.848	0.0275
0.868	0.027
0.9	0.0235

TYP2 and TYP3	
x/c	z/c
0.702	-0.0335
0.702	0.0285
0.858	0.0285
0.9	0.0235

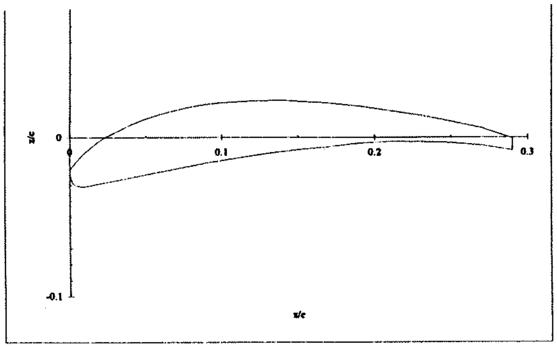
Co-ordinates of the back parts of the airfoils



Upper surface	
x/c	z/c
1	-0.0007
0.975	0.00609
0.95	0.01287
0.925	0.01961
0.9	0.02639
0.875	0.03315
0.85	0.03988
0.825	0.04646
0.8	0.05286
0.775	0.05907
0.75	0.06513
0.725	0.07092
0.7	0.07634
0.675	0.08136
0.65	0.08599
0.625	0.09006
0.6	0.09371
0.575	0.09668
0.55	0.0991
0.5	0.10258
0.45	0.10445
0.4	0.10491
0.35	0.104
0.3	0.1016
0.25	0.0977
0.2	0.092
0.175	0.0884
0.15	0.084
0.125	0.079
0.1	0.073
0.075	0.06551
0.05	0.05589
0.0375	0.04965
0.025	0.0417
0.0125	0.0307
0.005	0.0204
0.002	0.013
0	0

Lower surface	
x/c	z/c
0	0
0.002	-0.0093
0.005	-0.0138
0.0125	-0.0205
0.025	-0.0269
0.0375	-0.0319
0.05	-0.0358
0.075	-0.0421
0.1	-0.047
0.125	-0.051
0.15	-0.0543
0.175	-0.057
0.2	-0.0593
0.25	-0.0627
0.3	-0.0645
0.35	-0.0652
0.4	-0.0649
0.45	-0.0635
0.5	-0.061
0.55	-0.057
0.575	-0.054
0.6	-0.0508
0.625	-0.0469
0.65	-0.0428
0.675	-0.0384
0.7	-0.034
0.725	-0.0294
0.75	-0.0249
0.775	-0.0204
0.8	-0.016
0.825	-0.012
0.85	-0.0086
0.875	-0.0058
0.9	-0.0036
0.925	-0.0025
0.95	-0.0026
0.975	-0.004
1	-0.008

Co-ordinates of the GA(W)-1 airfoil

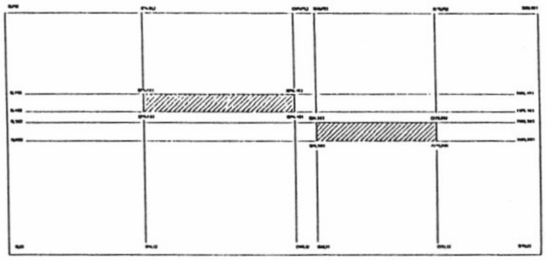


Upper surface	
x/c	z/c
0	-0.0235
0.0003	-0.02
0.002	-0.0179
0.004	-0.0155
0.008	-0.0113
0.012	-0.0078
0.018	-0.0033
0.023	0
0.028	0.0023
0.038	0.007
0.048	0.011
0.058	0.0141
0.068	0.0168
0.078	0.019
0.088	0.0207
0.098	0.0218
0.108	0.0223
0.118	0.0228
0.128	0.023
0.138	0.0234
0.148	0.0228
0.158	0.0223
0.168	0.0219
0.19	0.0198
0.21	0.0168
0.23	0.0138
0.25	0.0098
0.27	0.0059
0.29	-0.0007

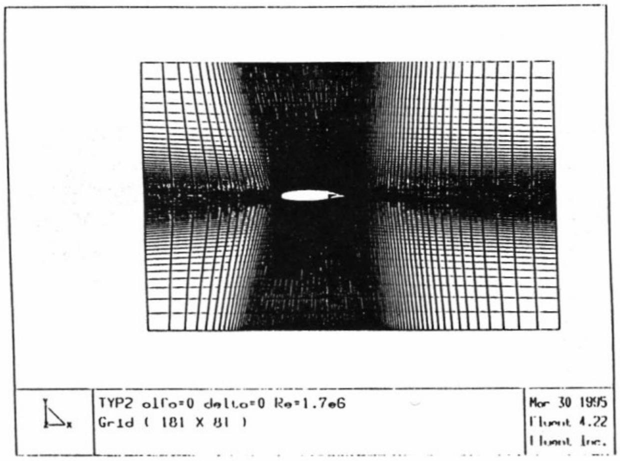
Lower surface	
x/c	z/c
0	-0.0235
0.001	-0.027
0.002	-0.0288
0.004	-0.03
0.008	-0.031
0.012	-0.0304
0.02	-0.0288
0.03	-0.027
0.05	-0.0235
0.07	-0.0198
0.09	-0.016
0.11	-0.013
0.13	-0.01
0.15	-0.0077
0.17	-0.0058
0.19	-0.0036
0.21	-0.0027
0.23	-0.0028
0.25	-0.0035
0.27	-0.005
0.29	-0.008

Co-ordinates of the Fowler flap

Appendix B

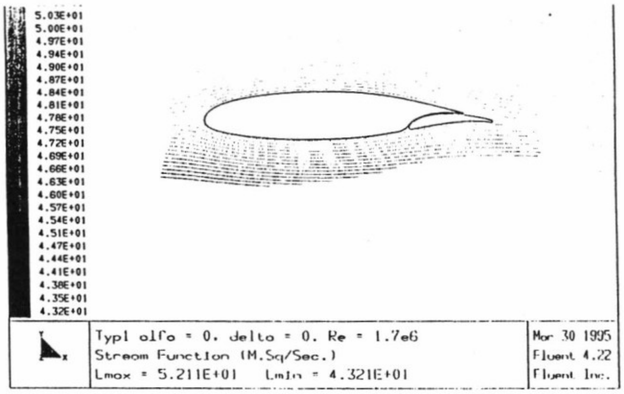


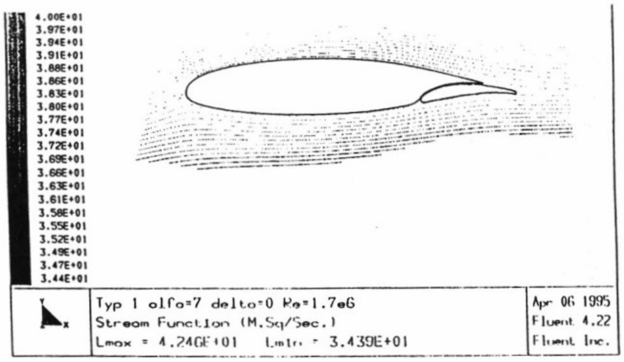
Example of a mathematical grid

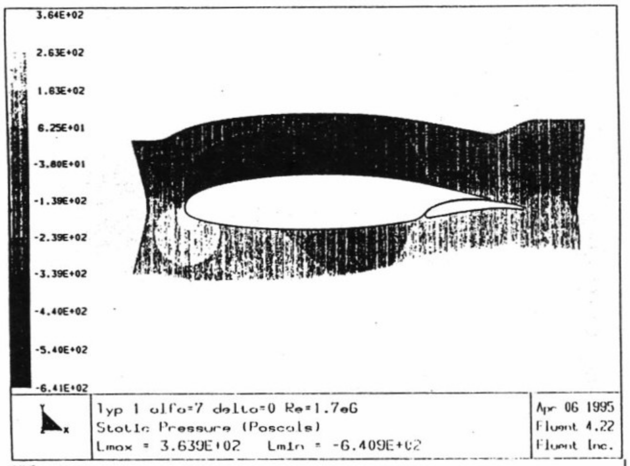


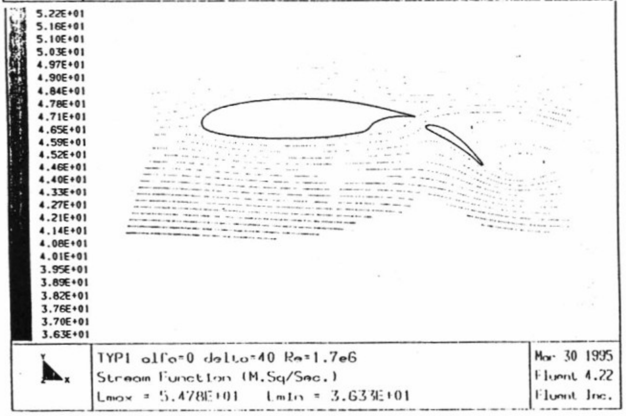
Example of a physical grid

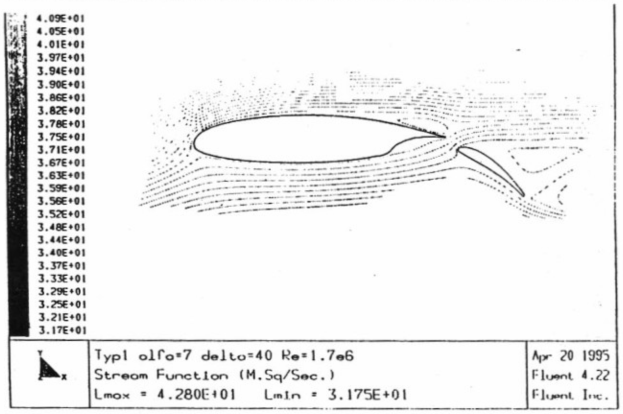
Appendix C

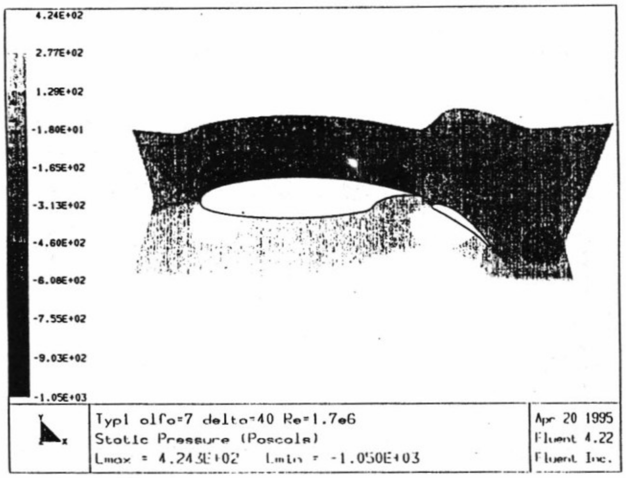


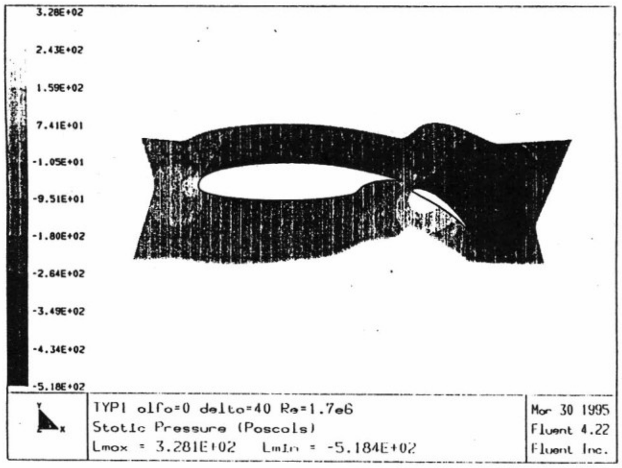




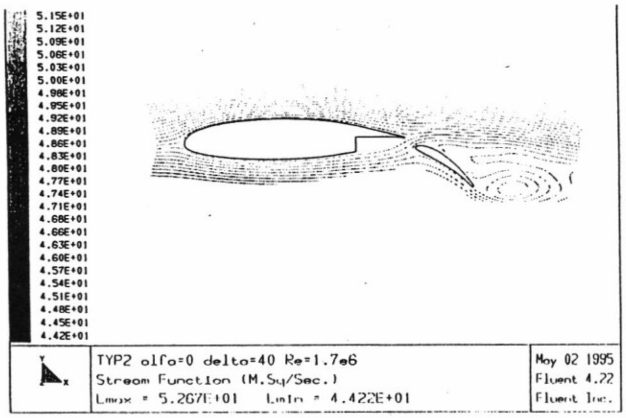








TYP1 alfa=0 delta=40 Re=1.7e6
Static Pressure (Pascals)
Lmax = 3.281E+02 Lmin = -5.184E+02
Mar 30 1995
Fluent 4.22
Fluent Inc.



TYP2 alfa=0 delta=40 Re=1.7e6
Stream Function (M.Sq/Sec.)
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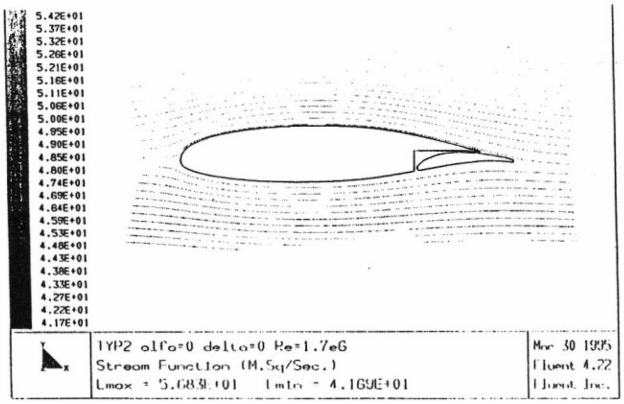
May 02 1995
Fluent 4.22
Fluent Inc.



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Stream Function (M.Sq/Sec.)
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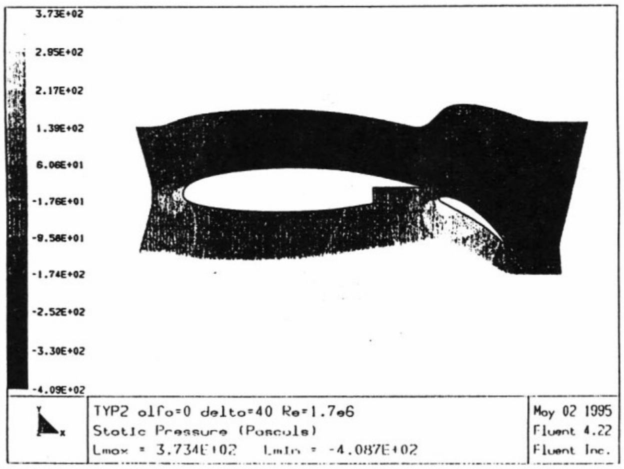
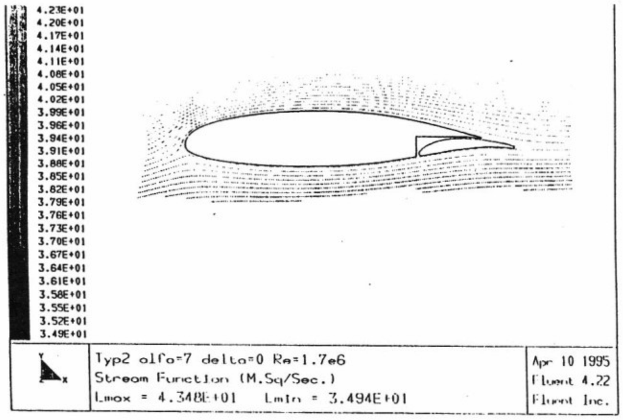
Fluent 4.22
Fluent Inc.



TYP2 alfa=0 delta=40 Re=1.7e6
Static Pressure (Pascals)
Lmax = 3.734E+02 Lmin = -4.087E+02
May 02 1995
Fluent 4.22
Fluent Inc.



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Stream Function (M.Sq/Sec.)
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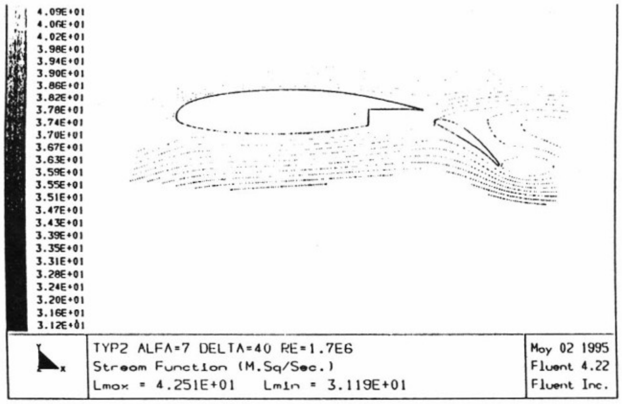
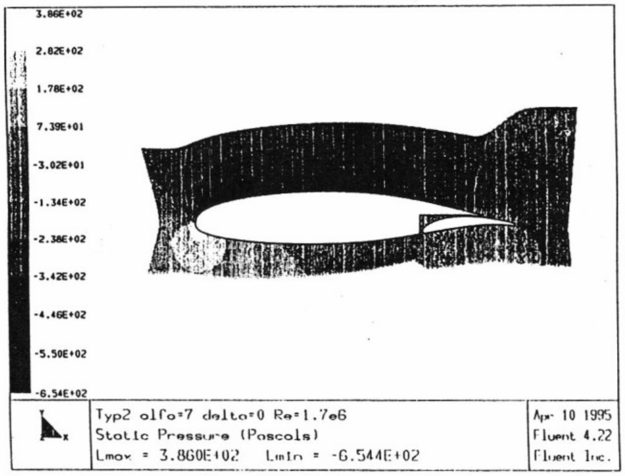
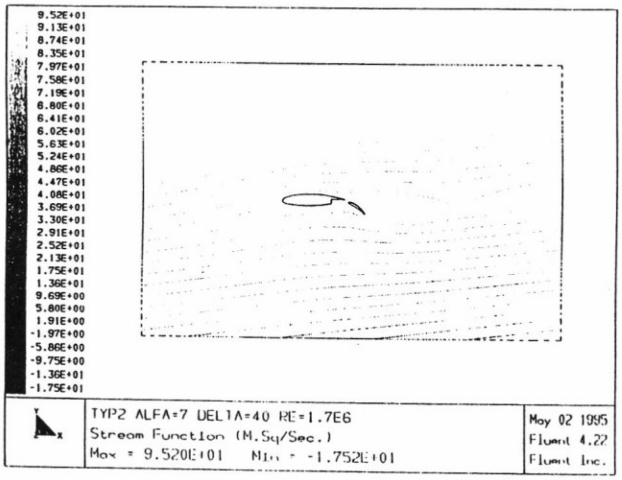
Apr 10 1995
Fluent 4.22
Fluent Inc.



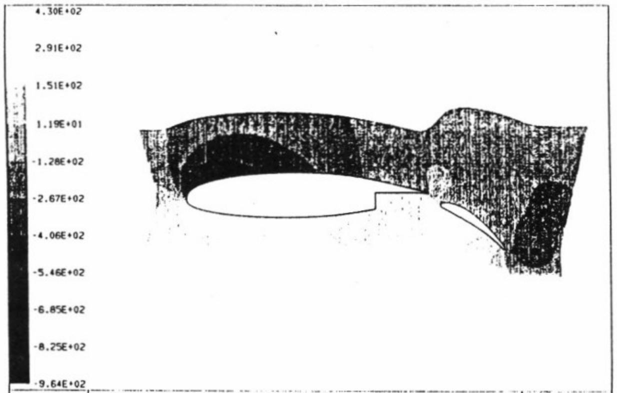
TYP2 ALFA=7 DELTA=40 RE=1.7E6
Stream Function (M.Sq/Sec.)
Lmax = 4.251E+01 Lmin = 3.119E+01
May 02 1995
Fluent 4.22
Fluent Inc.



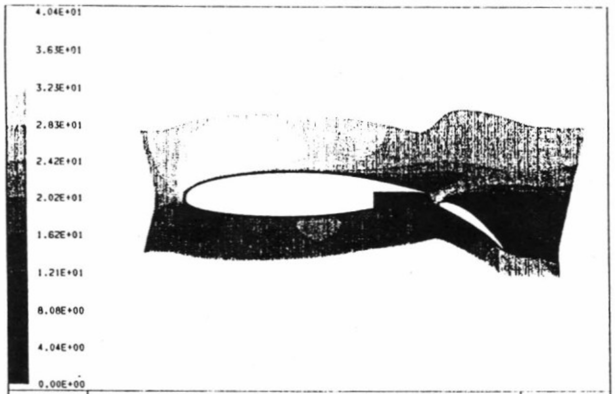
Typ2 alfa=7 delta=0 Re=1.7e6
Static Pressure (Pascals)
Lmax = 3.860E+02 Lmin = -6.544E+02
Apr 10 1995
Fluent 4.22
Fluent Inc.



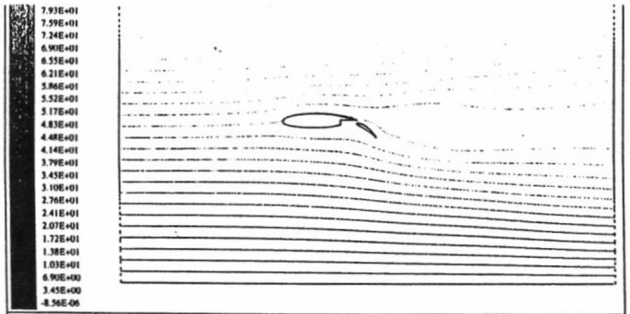
TYP2 ALFA=7 DELTA=40 RE=1.7E6
Stream Function (M.Sq/Sec.)
Max = 9.520E+01 Min = -1.752E+01
May 02 1995
Fluent 4.22
Fluent Inc.



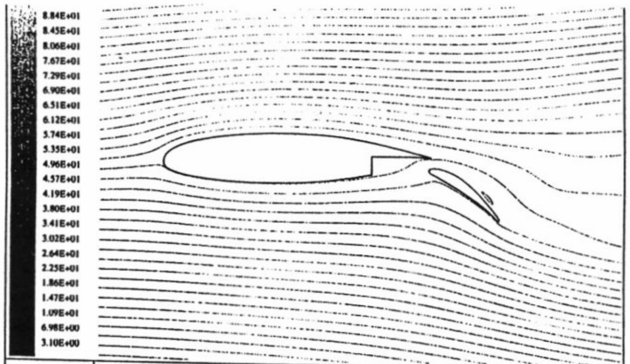
TYP2 ALFA=7 DELTA=40 RE=1.7E6 May 02 1995
Static Pressure (Poscols) Fluent 4.22
Lmax = 4.302E+02 Lmin = -9.641E+02 Fluent Inc.



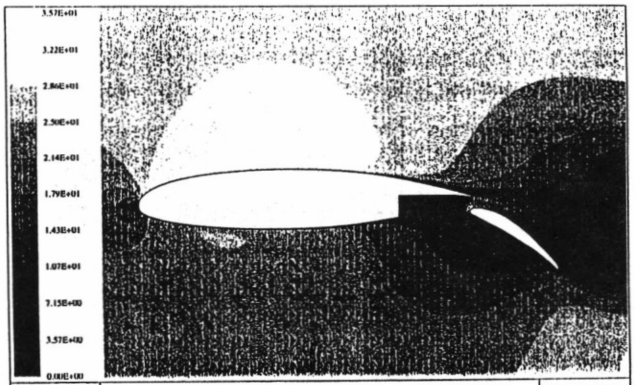
TYP2 ALFA=7 DELTA=40 RE=1.7E6 May 02 1995
Velocity Magnitude (Meters/Sec) Fluent 4.22
Lmax = 4.038E+01 Lmin = 0.000E+00 Fluent Inc.



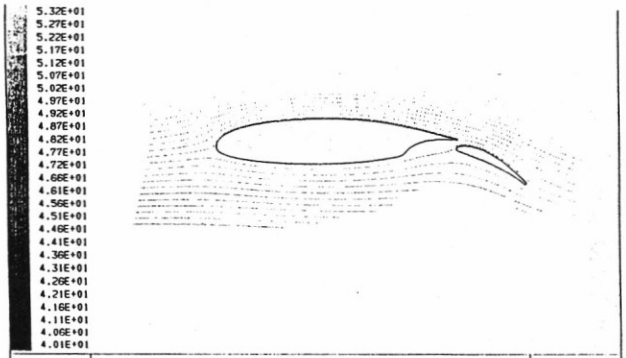
TYP3 alfa=0 delta=40 Re=1.7e6 Feb 13 1996
Stream Function (M2/S) Fluent 4.32
Max = 1.000E+02 Min = -8.564E-06 Fluent Inc.



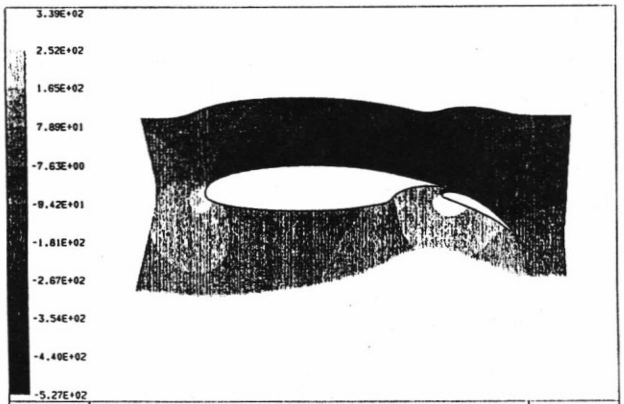
TYP3 alfa=0 delta=40 Re=1.7e6 Feb 13 1996
Stream Function (M2/S) Fluent 4.32
Max = 1.000E+02 Min = -8.564E-06 Fluent Inc.



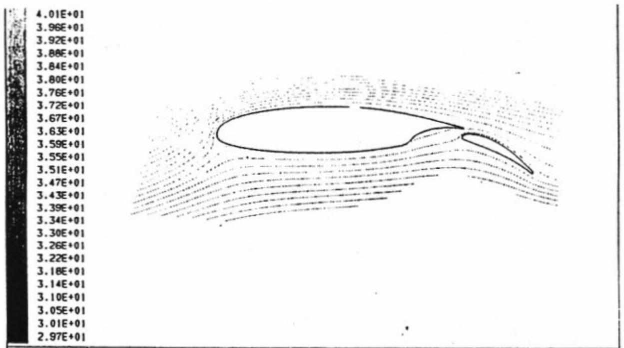
TYP3 alfa=0 delta=40 Re=1.7e6 Feb 13 1996
Velocity Magnitude (M/S) Fluent 4.32
Max = 3.574E+01 Min = 0.000E+00 Fluent Inc.



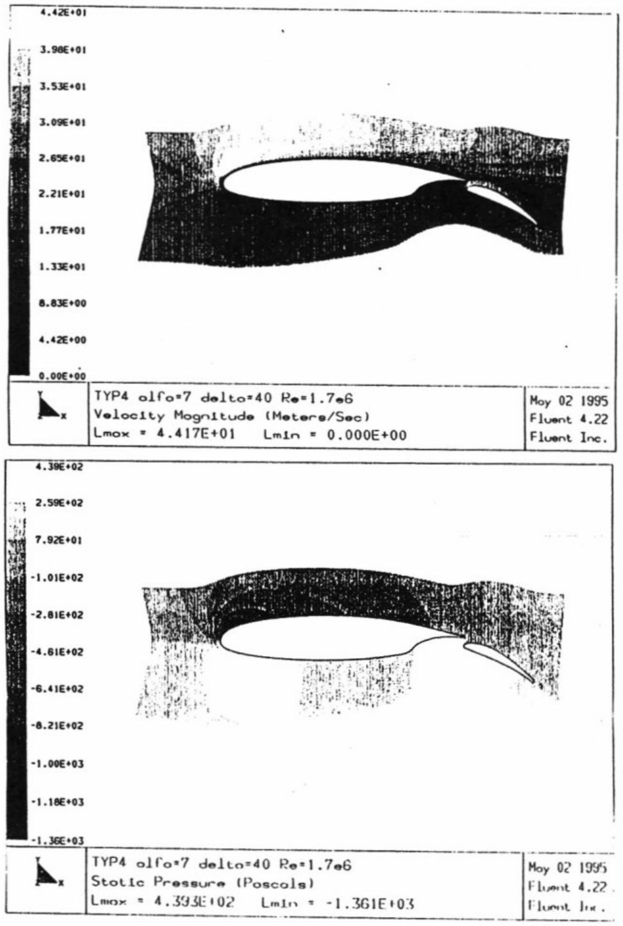
TYP4 alfa=0 delta=40 Re=1.7e6 May 02 1995
Stream Function (M.Sq/Sec.) Fluent 4.22
Lmax = 5.474E+01 Lmin = 4.008E+01 Fluent Inc.



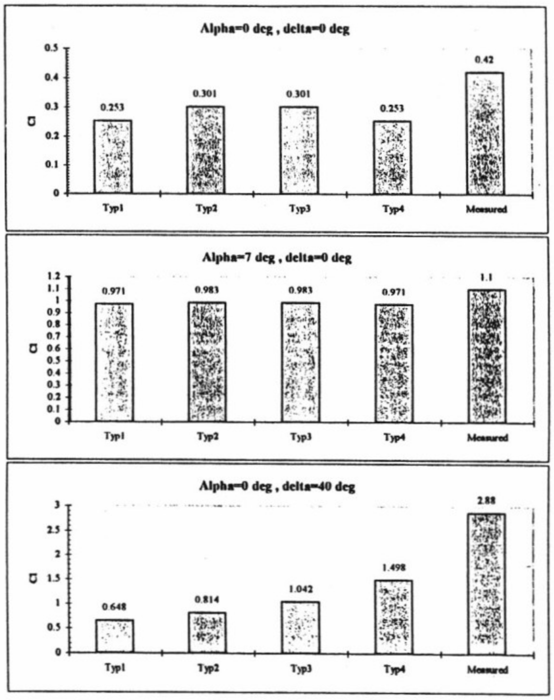
TYP4 alfa=0 delta=40 Re=1.7e6 May 02 1995
Static Pressure (Poscols) Fluent 4.22
Lmax = 3.386E+02 Lmin = -5.270E+02 Fluent Inc.

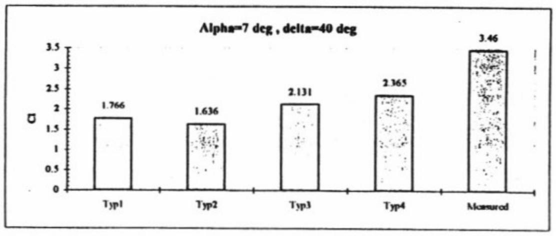


TYP4 alfa=7 delta=40 Re=1.7e6 May 02 1995
Stream Function (M.Sq/Sec.) Fluent 4.22
Lmax = 4.171E+01 Lmin = 2.972E+01 Fluent Inc.

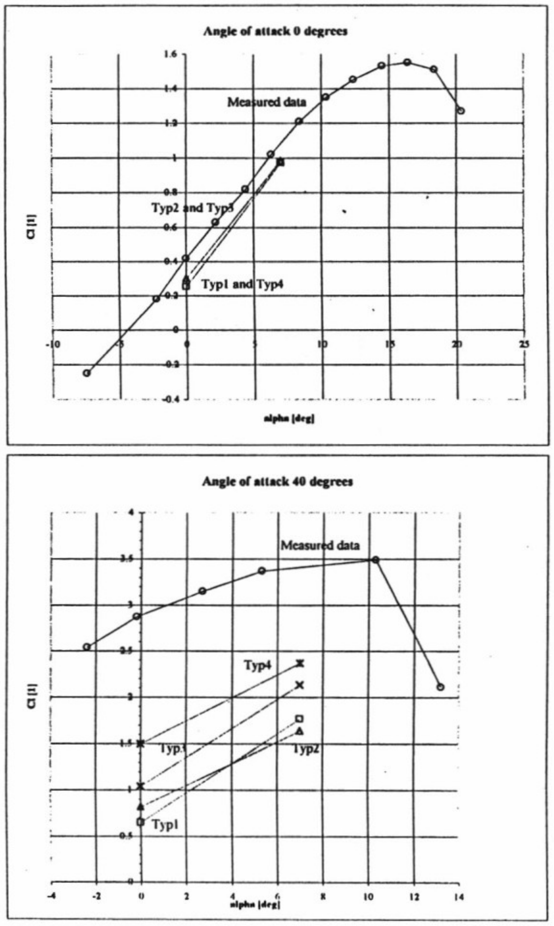


Calculation results of the flow around the airfoil with the Fowler flap





Compare of the lift coefficients



Compare the measured and the calculated data