Project Mach-2D-5.8
Revision report

Guilherme Bertoldo

September 25, 2011

This document presents the revision and subversion of the code Mach-2D-5.8. This code aims to implement parallel computation in the code Mach-2D-5.7, which was a revision of code Mach-2D-5.6 written for Linux OS.

As a need to implement parallel computation, the principal subroutines of Mach-2D-5.7 were rewritten with explicit reference to input and output variables. All subroutines and comments were translated to english to avoid codification mismatch.

Revision 001

In the coefficient module, the subroutine GetMetrics was implemented where some metrics are calculated using means. Maliska (book, 2nd ed., page 221) suggests to avoid this practice. So this revision intend to correct this point. All coordinates are calculated by interpolation, then derivatives are applied to calculate the metrics.

```
Test01
------
Tests were done using
x = 10 csi + 20 eta + csi eta
y = 30 csi - 40 eta - csi eta

No differences between analytic and numerical solution were found for
alpha-e
gamma-n
beta-e
beta-n
Je
Jn
Jp
when centroids are calculated by simple mean. Differences appears if
weighted mean is used.

Test02
------
Contains revision 007 of mach2d5.7-linux for further comparisons


Test03
------
Subroutine raios of Mach2D_5p7_coeficientes.f90 (rv007) was rewritten using the two methods.
The first method is the same as before and applies the central radius of two neighbours volumes
to calculate the radius of the fictitious one by extrapolation.
The second method applies the central radius of one neighbour and the radius at the face on the boundary
between the real neighbour and the fictitious volume to calculate the radius of the fictitious
volume by extrapolation.
No differences was found when the same method was applied, indicating no programming errors.
No differences was found up to the 10th figure in mass flow rate (fme) and drag (Fd) when the second method was
applied.


Test04
------
Subroutine metricas of Mach2D_5p7_coeficientes.f90 (rv007) was rewritten. In the metricas subroutine some
```

```
metrics on the boundary are calculated by interpolation. Maliska (book, 2nd ed. page 221) suggests to avoid
this practice.
The new subroutine GetMetrics was verified by comparing its results with analytic results.

No differences was caused by the new subroutine in the mass flow rate (fme) and drag (Fd) up to the eighth figure.

OBS.: It is necessary to study the influence of the metrics calculation on the final solution.

Test05
------
Subroutine x_y_nodal of Mach2D_5p7_coeficientes.f90 (rv007) was rewritten using two methods.
The first method calculates the coordinate of the centroid using a simple mean of the coordinates
of the corners of the volume. The second one divides the volume in two triangles, calculates the area
of each triangle and their centroids, then calculates the centroid of the volume by a weighted mean
based on the triangles area.

No differences in the results were found for the first method. This suggests no programming errors.

For the second method, differences appeared in the fifth figure of mass flow rate (fme) and drag (Fd).

Test06
-----
In the Test01 it was found differences in the results of metrics when centroids are calculated by
weighted mean. In order to search for errors, the centroids given by weighted mean was compared
with some results obtained anallyticaly in TM702 classes. No differences were found.
```

Revision 002

Subroutines massa_especifica_nos and massa_especifica_faces of Mach2D_5p7_coeficientes.f90 were rewritten. The new subroutines are called GetDensityAtNodes and GetDensityAtFaces, respectively, and are stored in module coefficients of mach2d-coef.f90.

```
Test01
------
Contains the files of revision 007 of Mach2D 5.7. Used only for comparison with modified subroutines

Test02
------
Contains the files of revision 007 of Mach2D 5.7 and mach2d-coef.f90. The new subroutines GetDensityAtNodes
 and GetDensityAtFaces
are used instead of massa_especifica_nos and massa_especifica_faces. No differences were found.
```

Revision 003

Subroutines coeficientes_velocidades and fonte_velocidade_u of Mach2D_5p7_coeficientes.f90 were rewritten. The new subroutines are called GetUxCoefficients and GetUxSource, respectively, and are stored in module coefficients of mach2d-coef.f90.

```
Test01
------
Contains the files of revision 007 of Mach2D 5.7. Used only for comparison with modified subroutines

Test02
------
Contains the files of revision 007 of Mach2D 5.7 and mach2d-coef.f90. The new subroutines
GetUxCoefficients and GetUxSource
are used instead of coeficientes_velocidades and fonte_velocidade_u. Differences in results appeared
due rounding errors.
```

Revision 004

Subroutine fonte_velocidade_v of Mach2D_5p7_coeficientes.f90 was rewritten. Two new subroutines were introduced. GetUyCoefficients is new and GetUySource replaces fonte_velocidade_v. Both subroutines are stored in module coefficients of mach2d-coef.f90.

```
Test01
------
Contains the files of revision 007 of Mach2D 5.7. Used only for comparison with modified subroutines

Test02
------
Contains the files of revision 007 of Mach2D 5.7 and mach2d-coef.f90. The new subroutines
 GetUyCoefficients and GetUySource
are used. The last one replaces fonte_velocidade_v. Differences in results appeared due rounding errors.
```

Revision 005

Subroutine coeficientes_fonte_temperatura of Mach2D_5p7_coeficientes.f90 was rewritten. The new subroutine GetTemperatureCoefficientsAndSource is stored in mach2d-coef.f90.

```
Test01
------
Contains the files of revision 007 of Mach2D 5.7. Used only for comparison with modified subroutines

Test02
------
Contains the files of revision 007 of Mach2D 5.7 and mach2d-coef.f90. The new subroutines
 GetTemperatureCoefficientsAndSource is used.
The last one replaces coeficientes_fonte_temperatura. Differences in results appeared due rounding errors.
```

Revision 006

Subroutine coeficientes_fonte_pressao of Mach2D_5p7_coeficientes.f90 was rewritten. The new subroutine GetPressureCoefficientsAndSource is stored in mach2d-coef.f90.

```
Test01
------
Contains the files of revision 007 of Mach2D 5.7. Used only for comparison with modified subroutines

Test02
------
Contains the files of revision 007 of Mach2D 5.7 and mach2d-coef.f90. The new subroutine
 GetPressureCoefficientsAndSource is used.
The last one replaces coeficientes_fonte_pressao. Differences in results appeared due rounding errors.
```

Revision 007

Subroutine velocidades_contravariantes_faces and coeficientes_SIMPLEC of Mach2D_5p7_coeficientes.f90 were rewritten. The new subroutines GetContravariantVelocityAtFaces and GetInternalSimplecCoefficients are stored in mach2d-coef.f90.

Modifications in velocidades_contravariantes_faces: in the subroutine velocidades_contravariantes_faces of Mach2D_5p7_coeficientes.f90, it was not attributed values to variables npsw and npse in the second loop. This was corrected in the revision 008 of Mach2D 5.7.

In subroutine velocidades_contravariantes_faces, the SIMPLEC coefficients due, dve, dun and dvn are calculated. In the new subroutine GetContravariantVelocityAtFaces this task is left to subroutine GetInternalSimplecCoefficients.

```
Test01
------
Contains the files of revision 008 of Mach2D 5.7. Used only for comparison with modified subroutines.

Test02
------
Contains the files of revision 008 of Mach2D 5.7 and mach2d-coef.f90. The new subroutines
 GetContravariantVelocityAtFaces
and GetInternalSimplecCoefficients are used instead of velocidades_contravariantes_faces and
 coeficientes_SIMPLEC.
Differences in results appeared due rounding errors.

OBS.: GetContravariantVelocityAtFaces needs cartesian velocities at corners.
```

Revision 008

Subroutine pressao_e_massa_especifica_com_pl, u_v_nos_reais_com_pl and Uce_Vcn_faces_internas_com_pl of Mach2D_5p7_coeficientes.f90 were rewritten. The new subroutines get_pressure_density_correction_with_pl, get_u_v_at_real_nodes_with_pl and get_velocities_at_internal_faces_with_pl are stored in mach2d-coef.f90.

```
Test01
------
Contains the files of revision 008 of Mach2D 5.7. Used only for comparison with modified subroutines.

Test02
------
Contains the files of revision 008 of Mach2D 5.7 and mach2d-coef.f90. The new subroutines
get_pressure_density_correction_with_pl, get_u_v_at_real_nodes_with_pl and
get_velocities_at_internal_faces_with_pl are used instead of pressao_e_massa_especifica_com_pl,
u_v_nos_reais_com_pl and Uce_Vcn_faces_internas_com_pl.


There are two ways of update density in get_pressure_density_correction_with_pl:
ro = ro + pl * g
or
ro = p * g
where g = 1/(Rg * T).
If the first way is used in subroutine get_pressure_density_correction_with_pl, the differences in final result,
relatively to pressao_e_massa_especifica_com_pl, arise from the 10th decimal place. On the other hand, if
if the second way is applied, only rounding errors are found. The second way was used.

When subroutine get_u_v_at_real_nodes_with_pl is used instead of u_v_nos_reais_com_pl only rouding errors
were found.

When get_velocities_at_internal_faces_with_pl is applied instead of Uce_Vcn_faces_internas_com_pl no
differences were found.
```

Revision 009

```
In order to clarify the usage of subroutines, some of them were renamed.

MODULE COEFFICIENTS:

OLD NAMES:
  !  1) GetRealCentroidsXY
  !  2) GetMetrics
  !  3) GetRadius
  !  4) GetDensityAtNodes
  !  5) GetDensityAtFaces
  !  6) GetUxCoefficients
  !  7) GetUxSource
  !  8) GetUyCoefficients
  !  9) GetUySource
  ! 10) GetTemperatureCoefficientsAndSource
  ! 11) GetPressureCoefficientsAndSource
  ! 12) GetContravariantVelocityAtFaces
  ! 13) GetInternalSimplecCoefficients
  ! 14) get_pressure_density_correction_with_pl
  ! 15) get_u_v_at_real_nodes_with_pl
  ! 16) get_velocities_at_internal_faces_with_pl

NEW NAMES:
  !  1) get_real_centroids_xy
  !  2) get_metrics
  !  3) get_radius
  !  4) get_density_at_nodes
  !  5) get_density_at_faces
  !  6) get_u_coefficients
  !  7) get_u_source
```

```
  !  8) get_v_coefficients
  !  9) get_v_source
  ! 10) get_T_coefficients_and_source
  ! 11) get_p_coefficients_and_source
  ! 12) get_velocities_at_faces
  ! 13) get_internal_simplec_coefficients
  ! 14) get_pressure_density_correction_with_pl
  ! 15) get_u_v_at_real_nodes_with_pl
  ! 16) get_velocities_at_internal_faces_with_pl

MODULE COEFFICIENTS HAS BEEN FINISHED!



MODULE DATA:

OLD NAMES:
  !  1) GetParameters
  !  2) AllocateVariables
  !  3) InitializeVariables

NEW NAMES:
  !  1) get_parameters
  !  2) allocate_variables
  !  3) initialize_variables


MODULE GRID:

OLD NAMES:
  !  1) GridGen
  !  2) UniformGrid
  !  3) BackwardGPGrid
  !  4) GetGPRatio

NEW NAMES:
  !  1) set_grid
  !  2) get_uniform_grid
  !  3) get_backward_GP_grid
  !  4) get_GP_ratio
```

Revision 010

```
Subroutines of module usuario of Mach2D_5p7_usuario.f90 were rewritten.

Test01
------
Contains the files of revision 008 of Mach2D 5.7. Used only for comparison with modified subroutines.

Test02
------

temperatura_da_parede replaced by set_wall_temperature

calor_especifico_e_gama replaced by set_cp_and_gamma

viscosidade_laminar_nos replaced by set_laminar_viscosity_at_nodes

viscosidade_laminar_faces replaced by get_laminar_viscosity_at_faces

condutividade_termica_nos replaced by set_thermal_conductivity_at_nodes

condutividade_termica_faces replaced by get_thermal_conductivity_at_faces
```

```
No changes in the results was observed due the replacement of subroutines.
No programming errors.
```

Revision 011

```
Test01
------
Contains the files of revision 008 of Mach2D 5.7. Used only for comparison with modified subroutines.

Test02
------
Subroutines of module usuario of Mach2D_5p7_usuario.f90 were rewritten.

ccu replaced by set_bcu
ccv replaced by set_bcv
ccp replaced by set_bcp
ccT replaced by set_bcT

In order to attend to the observation of revision 007, coefficients of the linear system for u and v are
 calculated in such  a way that u and v are calculated at fictitious corners by extrapolation.

No changes in the results was observed due the replacement of subroutines.
No programming errors.
```

Revision 012

```
Test01
------
Contains the files of revision 008 of Mach2D 5.7. Used only for comparison with modified subroutines.

Test02
------
Subroutines of module usuario of Mach2D_5p7_usuario.f90 were rewritten.

Tin_pin_entrada                replaced by   get_uin_vin_pin_Tin_Mw
plin_entrada_p_ficticio        replaced by   get_plin_and_p_fictitious
u_v_nos_ficticios_com_pl       replaced by   get_u_v_at_fictitious_nodes_with_pl
Uce_Vcn_de_dn_faces_contornos  replaced by   get_Uce_Vcn_de_dn_at_boundary_faces
Uce_Vcn_faces_contornos_com_pl replaced by   get_Uce_Vcn_at_boundary_faces_with_pl
EXATO_MACH_fluxo_massa         replaced by   get_isentropic_mass_flow
EXATO_MACH_newton              replaced by   get_mach_area
estimativa_inicial             replaced by   get_initial_guess

Only rouding errors were found.
```

Revision 013

```
module user:
get_mach_area - a conditional was inserted to ensure that when the area ratio = 1 then Mach = 1.
get_inital_guess - an error in the index of a vector was corrected.

module solvers:
Inserted subroutines
norm_l1_5d
norm_l1_9d
Comparing these suboutines with
norma_l1_5d
norma_l1_9d
of Mach2D5p6, only rounding errors were found.

At this revision the same results for mass flow rate and dynamic thrust of rv009 of Mach2D 5.7
were obtained provided metrics are calculated with get_metrics (metricas and get_metrics use different
methods to calculate metrics).
```

In other words, rv009 of Mach2D5p7 and present revision produce the same result.

Test01
Contains rv009 of Mach2D5p7 for comparison with other tests.

Test02
Contains rv009 of Mach2D5p7 with metricas replaced by get_metrics subroutine. Comparison between this modification of rv009 of Mach2D5p7 with present revision (rv013), shows that differences arise only by rouding errors.

Revision 014

Parallel computation was implemented using revision 013 and OpenMP.
Parallelization is used to calculate thermal and viscous properties, to calculate coefficients of linear systems for u and v and to solve these linear systems.

Test01
Contains rv013 for comparisons with rv014.
Comparing mass flow rate and dynamic thrust, differences appeared due rouding errors only.

Test02
When solver MSI was replaced by a TDMA solver (see revision 015 bellow), it was observed that mass flow rate and dynamic thrust suffered changes when parameters associated to the linear system of pressure correction, such as number of iteracions or tolerance, were changed. This test aims to quantify such changes. Seven simulations were run. The differences between simulations is a parameter associated to iteractions of the linear systems. The results are presented bellow:

DATA OF SIMULATION 1:

```
          S001 ....:  Simulation identification  (up to 100 characters)
            22 ....:  Number of real+ficititious volumes in the csi direction
            10 ....:  Number of real+ficititious volumes in the eta direction
             2 ....:  Kind of grid
 1.0000000E-03 ....:  Initial step for the geometric progression grid
             1 ....:  Coordinate system ( 1=cylindrical, else cartesian)
 2.8700000E+02 ....:  Perfect gas constant
 1.4000000E+00 ....:  gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 1.0000000E+06 ....:  Stagnation pressure in the chamber
 5.0000000E+02 ....:  Stagnation temperature in the chamber
 1.0000000E+00 ....:  Constant of the UDS/CDS mixing scheme
             1 ....:  modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
             1 ....:  ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
 1.0000000E-05 ....:  Time step
         10000 ....:  Maximum number of iteractions of the time evolution
             2 ....:  Maximum number of iteractions for the pressure correction
             5 ....:  Maximum number of iteractions for the MSI method for u, v and T
 1.0000000E-01 ....:  Tolerance for the MSI method for u, v and T
            10 ....:  Maximum number of iteractions for the MSI method for p
 1.0000000E-02 ....:  Tolerance for the MSI method for p
```

RESULTS OF SIMULATIONS

	it	norm / norm1	fmi	fme	Fd	diff. relative to S001
S001	10000	1.351191530930245E-09	5.678668617572837E+01	5.678668617572841E+01	2.982437587913622E+04	none
S002	10000	1.312730616567316E-09	5.678668617572841E+01	5.678668617572841E+01	2.982437587913619E+04	nitm_u = 10
S003	10000	5.043297097173190E-06	5.678668617572836E+01	5.678668617572841E+01	2.982437587913627E+04	tolu = 1.d-5
S004	10000	1.325729267781418E-09	5.678668618187415E+01	5.678668618187427E+01	2.982437542910004E+04	itmax = 4
S005 did not converge						itmax = 8
S006	10000	1.351191530930245E-09	5.678668617572837E+01	5.678668617572841E+01	2.982437587913622E+04	nitm_p = 20
S007	10000	1.264250970584168E-09	5.678668618681436E+01	5.678668618681429E+01	2.982437551831575E+04	tolp = 1.d-4

Note that when the number of iteractions (nitm_u) or tolerance (tolu) of linear systems for u, v and T are changed (S001-S003), the differences in the results are caused only by rouding errors. On the other hand, if the number of external iteractions (itmax) and tolerance (tolp) are changed for linear system of pressure correction, then the mass flow rate and thrust change from the 9th figure. No differences appeared in S006 because tolp finishes iteractions before nitm_p is reached.

Intending to evaluate the influence of the grid size on this results, more three simulations were performed (S008-S010):

```
DATA OF SIMULATION 8:
          S008 ....:  Simulation identification  (up to 100 characters)
            42 ....:  Number of real+ficititious volumes in the csi direction
            18 ....:  Number of real+ficititious volumes in the eta direction
             2 ....:  Kind of grid
 1.0000000E-03 ....:  Initial step for the geometric progression grid
             1 ....:  Coordinate system ( 1=cylindrical, else cartesian)
 2.8700000E+02 ....:  Perfect gas constant
 1.4000000E+00 ....:  gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 1.0000000E+06 ....:  Stagnation pressure in the chamber
 5.0000000E+02 ....:  Stagnation temperature in the chamber
 1.0000000E+00 ....:  Constant of the UDS/CDS mixing scheme
             1 ....:  modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
             1 ....:  ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
 5.0000000E-06 ....:  Time step
         10000 ....:  Maximum number of iteractions of the time evolution
             2 ....:  Maximum number of iteractions for the pressure correction
             5 ....:  Maximum number of iteractions for the MSI method for u, v and T
 1.0000000E-01 ....:  Tolerance for the MSI method for u, v and T
            10 ....:  Maximum number of iteractions for the MSI method for p
 1.0000000E-02 ....:  Tolerance for the MSI method for p

RESULTS OF SIMULATIONS
        it          norm / norm1                    fmi                     fme                      Fd    diff. relative to S008
S001 10000  1.351191530930245E-09  5.678668617572837E+01  5.678668617572841E+01  2.982437587913622E+04                  nx and ny
S008 10000  2.104156554023244E-09  5.677792729792442E+01  5.677792729792442E+01  2.982387558848702E+04                       none
S009 10000  1.953476906984203E-09  5.677792730044253E+01  5.677792730044254E+01  2.982387553809946E+04               tolp = 1.d-4
S010 10000  2.171127112735485E-09  5.677792729710496E+01  5.677792729710502E+01  2.982387547107686E+04                   imax = 4

Note that the same problem appears: results change from 9th figure.

Test03 and Test04

In order to study the time reduction of using parallel computation, the time needed
to solve a problem with the following parameters

           S01 ....:  Simulation identification  (up to 100 characters)
            42 ....:  Number of real+ficititious volumes in the csi direction
            18 ....:  Number of real+ficititious volumes in the eta direction
             2 ....:  Kind of grid
 1.0000000E-03 ....:  Initial step for the geometric progression grid
             1 ....:  Coordinate system ( 1=cylindrical, else cartesian)
 2.8700000E+02 ....:  Perfect gas constant
 1.4000000E+00 ....:  gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 1.0000000E+06 ....:  Stagnation pressure in the chamber
 5.0000000E+02 ....:  Stagnation temperature in the chamber
 1.0000000E+00 ....:  Constant of the UDS/CDS mixing scheme
             1 ....:  modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
             1 ....:  ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
 1.0000000E-05 ....:  Time step
         10000 ....:  Maximum number of iteractions of the time evolution
             2 ....:  Maximum number of iteractions for the pressure correction
             5 ....:  Maximum number of iteractions for the MSI method for u, v and T
 1.0000000E-01 ....:  Tolerance for the MSI method for u, v and T
            10 ....:  Maximum number of iteractions for the MSI method for p
 1.0000000E-02 ....:  Tolerance for the MSI method for p

was measued (three times) for one processor and two processors. The results are presented bellow

TIME CONSUMPTION USING TWO PROCESSORS

 2.2621489018027205E+01 .....: Time1 (s)
 2.2589501234004274E+01 .....: Time2 (s)
 2.2614214453962632E+01 .....: Time3 (s)
 ----------------------------------------
 Mean time = 22.6 s

TIME CONSUMPTION USING ONE PROCESSOR

 2.7378585043014027E+01 .....: Time1 (s)
 2.7386815523961559E+01 .....: Time2 (s)
 2.7380245146050584E+01 .....: Time3 (s)
 ----------------------------------------
 Mean time = 27.4 s
```

One can see that time reduction was about 17.5%.

These measured time refers to the one needed to solve the linear system iteratively.
(loop of the time evolution of the solving procedure)

Revision 015

Solver MSI of revision rv014 was replaced by a line-by-line TDMA method of 5 and 9 diagonals.

It was observed that:

1) For the linear systems of u, v and T: mass flow rate and dynamic thrust did not change when solver was replaced (only rouding errors were found).

2) For the linear system of pressure correction pl: mass flow rate and dynamic thrust CHANGED when solver was replaced. Changes occured from the 10th decimal place.
This change is related to the number of iteractions applied to solve the linear system.

3) The residual ratio L1_n/L1_1 changed significantly when the solver was changed for linear system of T.
This change is related to the number of iteractions applied to solve the linear system.

Test02 and Test03

In order to verify time optimization of parallel computation, some measurements were made. The procedure is similar to the one applied in revision 014. Parameters used:

```
  "S01" .....: sim_id - Simulation identification  (up to 100 characters)
      20 .....: nx-2   - Number of real volumes in the csi direction
       8 .....: ny-2   - Number of real volumes in the eta direction
       2 .....: kg     - Kind of grid (1=eta uniform, 2=geometric progression for eta)
   1.d-3 .....: a1     - Initial step for the geometric progression grid
       1 .....: coord  - Coordinate system ( 1=cylindrical, else cartesian)
  287.d0 .....: Rg     - Perfect gas constant
   1.4d0 .....: gamma  - gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 10.0d+5 .....: po     - Stagnation pressure in the chamber
  500.d0 .....: T0     - Stagnation temperature in the chamber
    1.d0 .....: beta   - Constant of the UDS/CDS mixing scheme
       1 .....: modvis - modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
       1 .....: ccTw   - ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
   1.d-5 .....: dt     - Time step
   10000 .....: itmax  - Maximum number of iteractions of the time evolution
       2 .....: imax   - Maximum number of iteractions for the pressure correction
       5 .....: nitm_u - Maximum number of iteractions for the TDMA method for u, v and T
      10 .....: nitm_p - Maximum number of iteractions for the TDMA method for p
```

Results are apresented bellow:

```
TIME CONSUMPTION USING TWO PROCESSORS
2.8339234838029370E+01 .....: Time1 (s)
2.8226870027021505E+01 .....: Time2 (s)
2.8235274304985069E+01 .....: Time3 (s)
---------------------------------------
Mean time 28.3 s


TIME CONSUMPTION USING ONE PROCESSOR
 3.8742839808983263E+01 .....: Time1 (s)
 3.8341871729004197E+01 .....: Time2 (s)
 3.8323719265987165E+01 .....: Time3 (s)
----------------------------------------
Mean time 38.5 s
```

Time reduction was about 26.5%. This efficiency is higher than that observed for MSI method.

Time measurements of this revision can not be compared to those of revision 014 because the number of iteractions are different.

Revision 016

Modification of the rv014 global algorithm: in the iterative solution of the linear system for the pressure correction, only the source term and boundary conditions are updated.

Code::Blocks is used as IDE.

It was found that the results do not depend on dt anymore.

GRID 1

```
   "S01" .....: sim_id - Simulation identification  (up to 100 characters)
      20 .....: nx-2   - Number of real volumes in the csi direction
       8 .....: ny-2   - Number of real volumes in the eta direction
       2 .....: kg     - Kind of grid (1=eta uniform, 2=geometric progression for eta)
   1.d-3 .....: a1     - Initial step for the geometric progression grid
       1 .....: coord  - Coordinate system ( 1=cylindrical, else cartesian)
  287.d0 .....: Rg     - Perfect gas constant
   1.4d0 .....: gamma  - gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 10.0d+5 .....: po     - Stagnation pressure in the chamber
  500.d0 .....: T0     - Stagnation temperature in the chamber
    1.d0 .....: beta   - Constant of the UDS/CDS mixing scheme
       1 .....: modvis - modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
       1 .....: ccTw   - ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
   1.d-7 .....: dt     - Time step
  500000 .....: itmax  - Maximum number of iteractions of the time evolution
       2 .....: imax   - Maximum number of iteractions for the pressure correction
       5 .....: nitm_u - Maximum number of iteractions for the MSI method for u, v and T
   1.d-1 .....: tolu   - Tolerance for the MSI method for u, v and T
      10 .....: nitm_p - Maximum number of iteractions for the MSI method for p
   1.d-2 .....: tolp   - Tolerance for the MSI method for p

   it              L1_N/L1_0     mass flow rate (in)    mass flow rate (out)                     Fd   dt
 6700   1.200833356147843E-09   5.678668618688039E+01   5.678668618688037E+01   2.982437551838925E+04   E-5
44700   2.060865231062360E-06   5.678668618688006E+01   5.678668618687961E+01   2.982437551838901E+04   E-6
*****   1.283540243530924E-02   5.678668618687591E+01   5.678668618687220E+01   2.982437551838311E+04   E-7
```

GRID 2

```
  "S04" .....: sim_id - Simulation identification  (up to 100 characters)
      50 .....: nx-2   - Number of real volumes in the csi direction
      40 .....: ny-2   - Number of real volumes in the eta direction
       2 .....: kg     - Kind of grid (1=eta uniform, 2=geometric progression for eta)
   1.d-3 .....: a1     - Initial step for the geometric progression grid
       1 .....: coord  - Coordinate system ( 1=cylindrical, else cartesian)
  287.d0 .....: Rg     - Perfect gas constant
   1.4d0 .....: gamma  - gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 10.0d+5 .....: po     - Stagnation pressure in the chamber
  500.d0 .....: T0     - Stagnation temperature in the chamber
    1.d0 .....: beta   - Constant of the UDS/CDS mixing scheme
       1 .....: modvis - modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
       1 .....: ccTw   - ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
   9.d-6 .....: dt     - Time step
  100000 .....: itmax  - Maximum number of iteractions of the time evolution
       8 .....: imax   - Maximum number of iteractions for the pressure correction
       5 .....: nitm_u - Maximum number of iteractions for the MSI method for u, v and T
   1.d-1 .....: tolu   - Tolerance for the MSI method for u, v and T
      10 .....: nitm_p - Maximum number of iteractions for the MSI method for p
   1.d-2 .....: tolp   - Tolerance for the MSI method for p

    it            norm / norm1                     fmi                     fme                     Fd      dt
 100000   1.936198862908188E-10   5.677840202523103E+01   5.677840202523105E+01   2.982345306844190E+04    9E-6
 100000   3.964047530452071E-07   5.677840202523078E+01   5.677840202523080E+01   2.982345306844167E+04    9E-7
 500000   3.601368373405795E-03   5.677840202524728E+01   5.677840202521814E+01   2.982345306839366E+04    9E-8
```

GRID 3

```
   "S01" .....: sim_id - Simulation identification  (up to 100 characters)
     100 .....: nx-2   - Number of real volumes in the csi direction
      80 .....: ny-2   - Number of real volumes in the eta direction
       2 .....: kg     - Kind of grid (1=eta uniform, 2=geometric progression for eta)
```

```
   1.d-3 .....: a1     - Initial step for the geometric progression grid
       1 .....: coord  - Coordinate system ( 1=cylindrical, else cartesian)
  287.d0 .....: Rg     - Perfect gas constant
   1.4d0 .....: gamma  - gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 10.0d+5 .....: po     - Stagnation pressure in the chamber
  500.d0 .....: T0     - Stagnation temperature in the chamber
    1.d0 .....: beta   - Constant of the UDS/CDS mixing scheme
       1 .....: modvis - modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
       1 .....: ccTw   - ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
   9.d-6 .....: dt     - Time step
 1000000 .....: itmax  - Maximum number of iteractions of the time evolution
       8 .....: imax   - Maximum number of iteractions for the pressure correction
       5 .....: nitm_u - Maximum number of iteractions for the MSI method for u, v and T
   1.d-1 .....: tolu   - Tolerance for the MSI method for u, v and T
      10 .....: nitm_p - Maximum number of iteractions for the MSI method for p
   1.d-2 .....: tolp   - Tolerance for the MSI method for p
```

it	norm / norm1	fmi	fme	Fd	dt
100000	6.362339528296163E-11	5.677857069917401E+01	5.677857069917400E+01	2.982220075339333E+04	9E-6
500000	9.511188338297630E-08	5.677857069917421E+01	5.677857069917417E+01	2.982220075339388E+04	9E-7
530300	7.296501011656949E-04	5.677857069918527E+01	5.677857069918247E+01	2.982220075340243E+04	9E-8

Revision 017

Modification of revision rv016. A new equation for pressure correction was implemented.

The new vectors Ucem, Vcnm were define to store the Uce and Vcn of the previous iteraction.

In the module mach2d-user, subroutine get_Uce_Vcn_de_dn_at_boundary_faces was split in get_boundary_simplec_coefficients and get_Uce_Vcn_at_boundary_faces.

In the subroutine get_pressure_density_correction_with_pl of module mach2d-coef.f90, density correction as ro = ro* + g*pl or ro=g*p produce the same results. In rv008, it was observed that the two ways produced different results. Now, the first way is applied.

The order of some subroutines were changed.

```
NEW ALGORITHM
-------------

Initializes all the variables to zero.
Defines the boundary nodes.
Generates the grid based on the boundary nodes.
Calculates the centroids of all real volumes.
Calculates the metrics.
Calculates the radius at the volume faces and centre.
Sets the wall temperature (for non-adiabatic walls only).
Variables initialization based on the 1D isentropic flow.

Starts the time evolution cycle
  Updates all the fields.
  Updates boundary data on the nozzle entrance.
  Calculates Cp and Gamma at the center of each volume.
  Calculates viscosity and thermal conductivity at centroids.
  Calculates viscosity and thermal conductivity at faces of each volume using the Patankar method.
  Calculates the coefficients and source of linear systems for u and v based on the data of the previous iteraction.
  Calculates the boundary conditions for u and v.
  Calculates the SIMPLEC coefficients.
  Calculates the coefficients of the pressure equation.
  Solves the equations for u and v. (This solution does not satisfy the mass equation)
  Calculates the cartesian and contravariant velocities at faces.
  Calculates the source term of the pressure equation.

  Starts the mass correction cycle
     Calculates the boundary condition of the pressure equation.
     Solves the equation for the pressure correction.
  Ends the mass correction cycle
```

```
  Corrects the pressure and specific mass with the pressure deviation.
  Corrects the velocities at centroids.
  Corrects the cartesian and contravariant velocities at volume faces.
  Calculates the specific mass at faces based on the corrected specific mass and velocities.
  Calculates the coefficients and source of the temperature equation.
  Calculates the boundary conditions of the temperature.
  Solves the temperature equation.
  Calculates specific mass at centroids using the new values of p and T and the state equation.
  Calculates the specific mass at faces based on the corrected specific mass and velocities.

  Error analisys.

Ends of time evolution cycle

Post processing.

Test01
           S01 ....:  Simulation identification  (up to 100 characters)
            22 ....:  Number of real+ficititious volumes in the csi direction
            10 ....:  Number of real+ficititious volumes in the eta direction
             2 ....:  Kind of grid
 1.0000000E-03 ....:  Initial step for the geometric progression grid
             1 ....:  Coordinate system ( 1=cylindrical, else cartesian)
 2.8700000E+02 ....:  Perfect gas constant
 1.4000000E+00 ....:  gamma = Cpo / Cvo in the chamber (Specific heat ratio)
 1.0000000E+06 ....:  Stagnation pressure in the chamber
 5.0000000E+02 ....:  Stagnation temperature in the chamber
 1.0000000E+00 ....:  Constant of the UDS/CDS mixing scheme
             1 ....:  modvis = 0 -> Euler;  modvis = 1 -> Navier-Stokes
             1 ....:  ccTw = 0 -> adiabatic;  ccTw = 1 -> prescribed temperature
 9.0000000E-06 ....:  Time step
          5000 ....:  Maximum number of iteractions of the time evolution
             8 ....:  Maximum number of iteractions for the pressure correction
             5 ....:  Maximum number of iteractions for the MSI method for u, v and T
 1.0000000E-01 ....:  Tolerance for the MSI method for u, v and T
            10 ....:  Maximum number of iteractions for the MSI method for p
 1.0000000E-02 ....:  Tolerance for the MSI method for p
```

it	norm / norm1	fmi	fme	Fd	dt
5000	1.711421489285850E-09	5.678668618688051E+01	5.678668618688041E+01	2.982437551838931E+04	9E-6
50000	2.851253845665069E-06	5.678668618687895E+01	5.678668618687980E+01	2.982437551839050E+04	9E-7
500000	2.400199927648853E-02	5.678668618687410E+01	5.678668618687441E+01	2.982437551837889E+04	9E-8