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ANALYSIS OF FLIGHT LOADS AND STATIC AEROELASTICITY CHARACTERISTICS OF THE AIRPLANE WITH THE USE OF THREE-DIMENSIONAL AERODYNAMICS

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Abstract: Flight loads are the main factor that defines strength of the airplane units. In common case, trim parameters and maneuvering loads (for static aeroelasticity) within MSC.Nastran are evaluated by doublet lattice method. Flat aerodynamics approach influences on the computational accuracy. The goal of the research is improvement of the problem using three-dimensional aerodynamic data obtained from computational fluid dynamics. The passenger airplane as an example is considered. The distribution of aerodynamic forces on wetted surfaces is computed within Fluent. Using MSC.Nastran Hybrid Static Aeroelasticity Toolkit, these three-dimensional aerodynamic mesh and aerodynamic forces at the nodes are imported in the design model. Analysis of trim parameters and flight loads in MSC.Nastran is performed.

1 INTRODUCTION

Flight loads are the main factor that defines strength of the airplane units. In common case, trim parameters and maneuvering loads within MSC.Nastran are evaluated by doublet lattice method (DLM) using flat steady aerodynamic theory. Flat aerodynamics approach influences on the computational accuracy.

The need to expand the methodological basis for calculating the flight loads caused by the use of non-classical aircraft configurations such as flying wing, with V-shaped fins, etc.

Computational fluid dynamics (CFD) methods are used as more accurate sources of data on aerodynamics.

MSC Nastran Hybrid Static Aeroelasticity (HSA) Toolkit is developed [1] to use CFD results of three-dimensional aerodynamic models (in this study using Fluent), which need to define trim parameters and flight loads in MSC.Nastran/MSC.FlightLoads, based on the finite element method.

The **research goal** is improvement of aerodynamic part of the problem of trim analysis and flight loads analysis using three-dimensional aerodynamic data obtained from CFD approach.

2 BASIC EQUATIONS

Before describing the new process, the governing equations are briefly discussed [2, 3, 4, 5, 6]. The general form of the aeroelastic trim problem is given by the equation (1):

$$[M_{gg}][\ddot{u}_g] + ([K_{gg}] - \bar{q}[Q_{gg}])[u_g] = (\bar{q}[Q_{gv}] + [P_{gv}])[u_v] \qquad (1)$$

where u_g is the vector of generalized coordinates, M_{gg} and K_{gg} are the mass and stiffness matrices and:

$$Q_{gg} = G^p_{gk} Q_{kk} G^d_{kg} \qquad (2)$$

is the aeroelastic influence matrix that is a combination of the aerodynamic influence coefficient matrix Q_{kk} and the spline matrices that convert structural displacements to aerodynamic displacements (G^d_{kg}) and aerodynamic forces to structural forces (G^p_{gk}). The matrices on the left hand side of equation (1) are derived from the flexible model. The right hand side of equation (1) contains a u_v term which represents the aerodynamic states.

Two types of rigid loads are considered. The first due to aerodynamics is given by:

$$Q_{gv} = G^p_{gk} Q_{kv} \qquad (3)$$

where Q_{kv} contains rigid loads produced from CFD or wind tunnel sources, and

$$P_{gv} = q P^q_{gv} + P^o_{gv} \qquad (4)$$

contains the non-aerodynamic controller forces such as engine thrust.

3 PROCESS DESCRIPTION

An overview of the new hybrid static aeroelastic (MSC.Nastran SOL 144+HSA) process is presented in Figure 3.1.

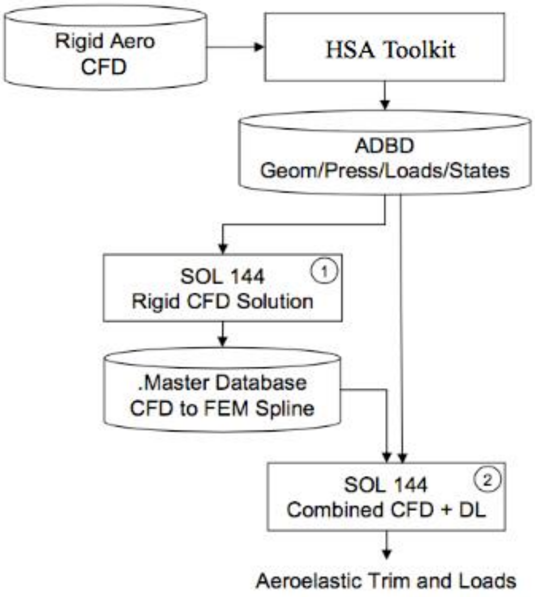


Figure 3.1: CFD/Doublet Lattice Process for Static Aeroelastic Analysis

The process begins with creation of the rigid aerodynamic data. A wide variety of linear or non-linear aerodynamic sources can be accommodated. These may include, CFD, wind tunnel, or panel codes.

Once the rigid CFD data is available, it is processed to obtain the rigid aerodynamic database ADBD using the Hybrid Static Aeroelasticity Toolkit (HSA). The purpose of this program is to convert and store the rigid aerodynamic and associated data into data blocks necessary for the MSC Nastran aeroelastic solution sequence. All solutions share the same aerodynamic mesh, but differ in the solution state. (i.e. Mach number, angle of attack, and control deflection…).

The main steps of the method are the following:

1. Export of CFD data - three-dimensional grid and aerodynamic forces on the wing model – from Fluent.

2. Creation and verification of the mathematical model of airplane (with flat aerodynamics).

3. Trim analysis of rigid airplane with DLM aerodynamics, using MSC.Nastran solution SOL144 (Static Aeroelasticity). Export of the flat aerodynamic grid and aerodynamic forces on the tail model to HSA Toolkit.

4. The use of HSA Toolkit to import CFD data in MSC.Nastran. Creation of the mathematical model of the airplane (with three-dimesional aerodynamics), verification of the loads.

5. Trim analysis of rigid airplane with the three-dimensional aerodynamic mesh, using option SOL144 Rigid Trim, see (1) on Figure 1.

6. Trim analysis of elastic airplane taking into account the results of p.5 for Rigid Trim and using flat aerodynamic approach for calculating flexible increments of flight loads, by applying the option SOL144 Flexible Trim, see (2) on Figure 1.

7. Evaluation of results.

4 OBJECT OF RESEARCH

As an example the passenger airplane with high aspect ratio wing, T-tail and tail-mounted engines is selected.

The airplane is in a trimmed level flight. Flight conditions are M = 0.83, H = 9300 m, vertical load factor $n_y = 1$, dynamic pressure q = 14200 Pa. Trim variables are the angle of attack, the angle of the elevator.

5 EXAMPLE OF SOLUTION

5.1 CFD data from Fluent to HSA Toolkit

Three-dimensional aerodynamic wing model is prepared based on theoretic geometry and performed with FEM in Fluent by Parasolid format geometry export, Figure 5.1.1. The distribution of aerodynamic forces and pressures on wetted surfaces is computed within Fluent, Figure 5.1.2.

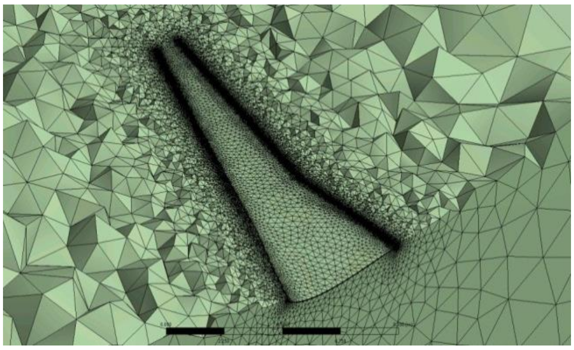


Figure 5.1.1: CFD FEM model of the three-dimensional wing

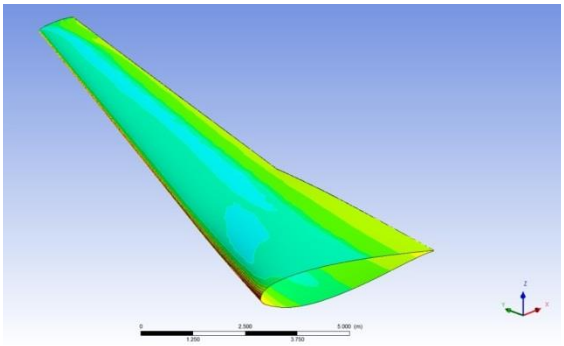


Figure 5.1.2: Distribution of aerodynamic pressures within CFD

The CFD data export file is made in MSC.Nastran format (aerodynamic mesh - nodes and finite elements and forces on grids). Import into the MSC.FlightLoads is made by HSA Toolkit.

5.2 Mathematical Models

The structure is represented by the system of crossed non-uniform beams, acting in bending and torsion, with distributed masses and inertia moments. In such case, beam model provides enough accuracy for estimation of normal modes. Symmetry conditions are specified for mathematical models in the plane XOZ [7].

Aerodynamic models: first – flat by applying DLM approach made by MSC.FlightLoads (see p.2-3 in Section 4 above), Figure 5.2.1; second - by applying non-linear (CFD) approach made by HSA Toolkit and MSC.FlightLoads, Figure 5.2.2.

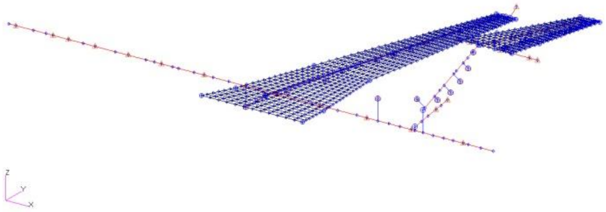


Figure 5.2.1: FEM structure with DLM aerodynamics

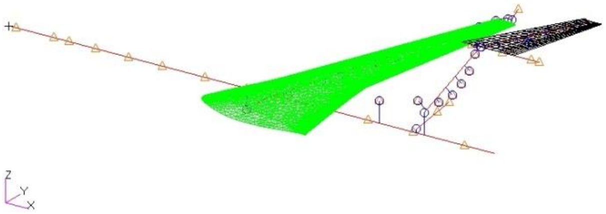


Figure 5.2.2: FEM structure with 3D aerodynamics

5.3 CFD Database Import and Spline Technologies

Within applied MSC Nastran HSA Toolkit, these three-dimensional aerodynamic mesh and aerodynamic forces at the nodes are imported in the design model.

A key feature of the HSA Toolkit is the ability to convert CFD rigid pressures into an equivalent aerodynamic force vector called DMIK (Direct Matrix Input) and then transfer that load to the target structure by employing the 6DOF spline. This approach ensures that the CFD load is conserved when transferred to the structure in terms of forces and moments, interpolate aerodynamic data from one mesh to another [6].

This can be useful for reducing storage and computational requirements by applying CFD results from a very fine mesh to a reduced-density mesh more appropriate for structural analysis.

There are five load cases was prepared for HSA in the CFD environment (Fluent) for the three-dimensional aerodynamic model. These load cases is define the range of angles of attack from 0 to 4 degrees.

28 Spline cards have been automatically created by using the Toolkit: 14 Splines for Force, 14 Splines for Displacements, shown on Figure 5.3.2.

The CFD load is conserved when mapped on the structure. Run time saving is decreased from about 25 minutes to 3 minutes.

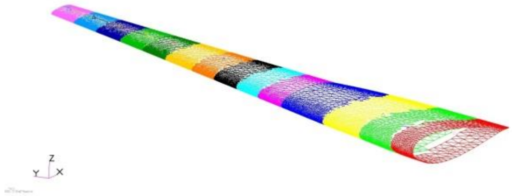


Figure 5.3.2: 3D aerodynamic groups for splines

5.4 Trim Analysis Procedure

The main purpose of this analysis, however, is to produce an MSC.Nastran database that contains the CFD spline information for input into the second SOL 144 analysis (flex trim), which is used to compute an aeroelastic solution from CFD and DLM data.

The Flexible Model input for the second SOL 144 run contains the Doublet-Lattice model used to provide aeroelastic corrections, and any desired rigid aerodynamic data not available from the CFD analyses. This file also contains the spline data for transferring the Doublet-Lattice results to the structure and the structural displacements to the Doublet-Lattice downwash points.

A feature of the separate aerodynamic mesh developments is that the set of controllers for the two meshes does not need to be the same. The flexible mesh is allowed to have additional controllers not contained in the CFD data. This provides an optional way of adding additional states not easily computed from CFD methods. An example of this would be adding states due to vehicle roll, pitch, and yaw rotations. These are easily created in MSC Nastran using the DLM, but are not easily developed from a CFD analysis. Additionally, the flexible mesh could be used to supply additional rigid control surface data that are not defined in the CFD model. In this case, both the rigid load and the elastic corrections would come from the Doublet-Lattice model.

The trim process involves specifying a maneuver in terms of Mach number, dynamic pressure and the prescribed control parameters (e.g., accelerations and rates). In standard SOL 144, the calculation of the trim state is a simple matter of solving a set of linear equations where the number of unknowns is equal to the number of rigid body degrees of freedom of the structure. This is performed under the restriction that the aerodynamics are a linear function of the control settings. For CFD applications, the trim algorithm needs to support a nonlinear solution since, unlike the Doublet-Lattice procedure, the aerodynamics can be a nonlinear function of any of the states such as angle of attack, sideslip, and control deflection. Figure 5.4.1 shows the nonlinear trim loop.

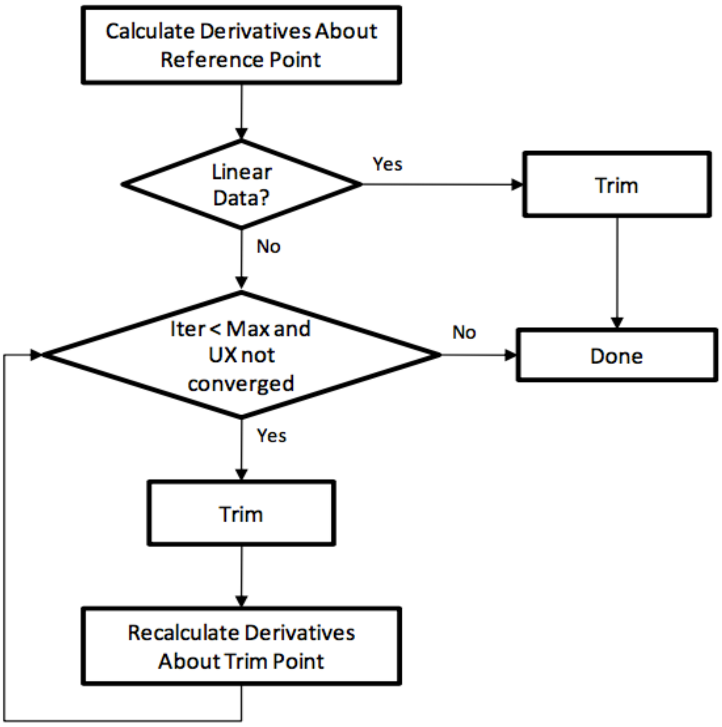
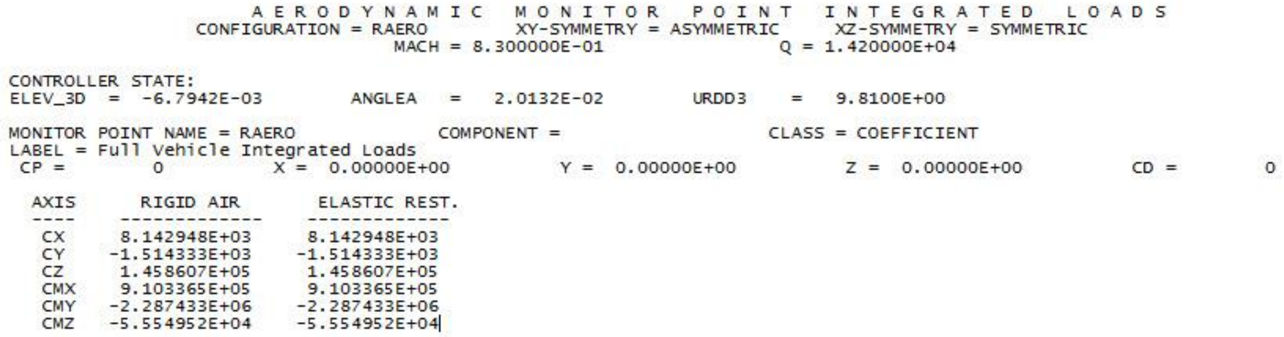


Figure 5.4.1: Nastran Nonlinear Trim Loop

6 RESULTS

Result forces on airplane as results of trim analysis, Figure 6.1, 6.2.



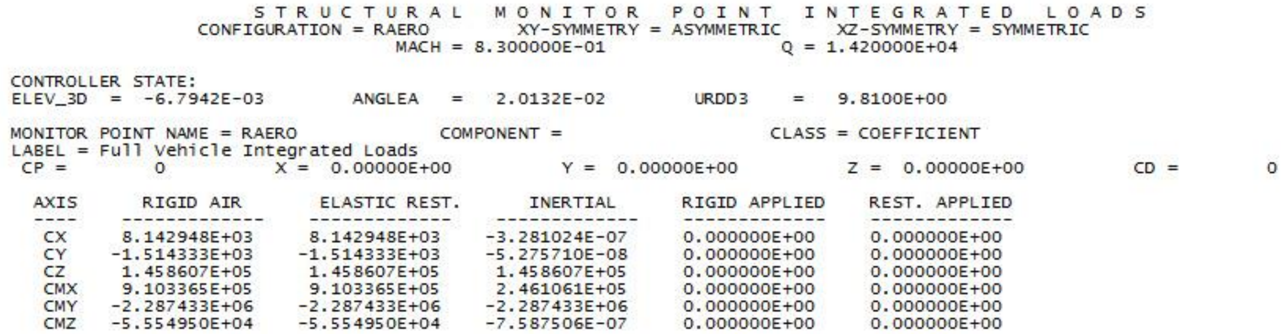
```
                A E R O D Y N A M I C   M O N I T O R   P O I N T   I N T E G R A T E D   L O A D S
            CONFIGURATION = RAERO         XY-SYMMETRY = ASYMMETRIC     XZ-SYMMETRY = SYMMETRIC
                              MACH = 8.300000E-01                       Q = 1.420000E+04

CONTROLLER STATE:
ELEV_3D   =   -6.7942E-03         ANGLEA    =    2.0132E-02         URDD3     =    9.8100E+00

MONITOR POINT NAME = RAERO                COMPONENT =                              CLASS = COEFFICIENT
LABEL = Full Vehicle Integrated Loads
 CP =           0          X =  0.00000E+00           Y =  0.00000E+00           Z =  0.00000E+00           CD =           0

  AXIS       RIGID AIR        ELASTIC REST.
  ----     -------------     -------------
   CX       8.142948E+03      8.142948E+03
   CY      -1.514333E+03     -1.514333E+03
   CZ       1.458607E+05      1.458607E+05
   CMX      9.103365E+05      9.103365E+05
   CMY     -2.287433E+06     -2.287433E+06
   CMZ     -5.554952E+04     -5.554952E+04
```

Figure 6.1: Result forces on aerodynamic model



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            CONFIGURATION = RAERO         XY-SYMMETRY = ASYMMETRIC     XZ-SYMMETRY = SYMMETRIC
                              MACH = 8.300000E-01                       Q = 1.420000E+04

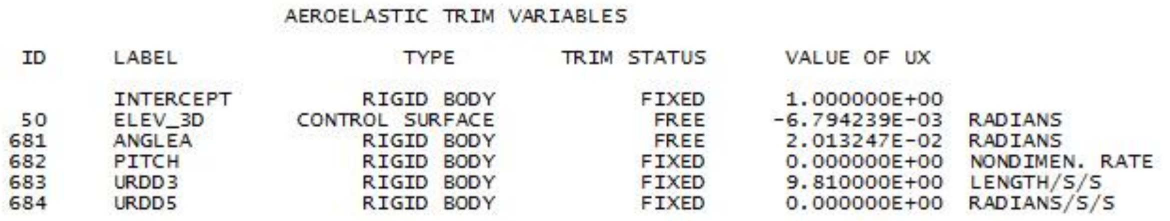
CONTROLLER STATE:
ELEV_3D   =   -6.7942E-03         ANGLEA    =    2.0132E-02         URDD3     =    9.8100E+00

MONITOR POINT NAME = RAERO                COMPONENT =                              CLASS = COEFFICIENT
LABEL = Full Vehicle Integrated Loads
 CP =           0          X =  0.00000E+00           Y =  0.00000E+00           Z =  0.00000E+00           CD =           0

  AXIS       RIGID AIR        ELASTIC REST.       INERTIAL        RIGID APPLIED      REST. APPLIED
  ----     -------------     -------------     -------------     -------------     -------------
   CX       8.142948E+03      8.142948E+03     -3.281024E-07     0.000000E+00      0.000000E+00
   CY      -1.514333E+03     -1.514333E+03     -5.275710E-08     0.000000E+00      0.000000E+00
   CZ       1.458607E+05      1.458607E+05      1.458607E+05     0.000000E+00      0.000000E+00
   CMX      9.103365E+05      9.103365E+05      2.461061E+05     0.000000E+00      0.000000E+00
   CMY     -2.287433E+06     -2.287433E+06     -2.287433E+06     0.000000E+00      0.000000E+00
   CMZ     -5.554950E+04     -5.554950E+04     -7.587506E-07     0.000000E+00      0.000000E+00
```

Figure 6.2: Result forces on structural model

The aeroelastic trim variables obtained as results shown on Figures 6.3, 6.4 (Rigid Trim case) and on Figures 6.5, 6.6 (Flexible Rigid Trim).

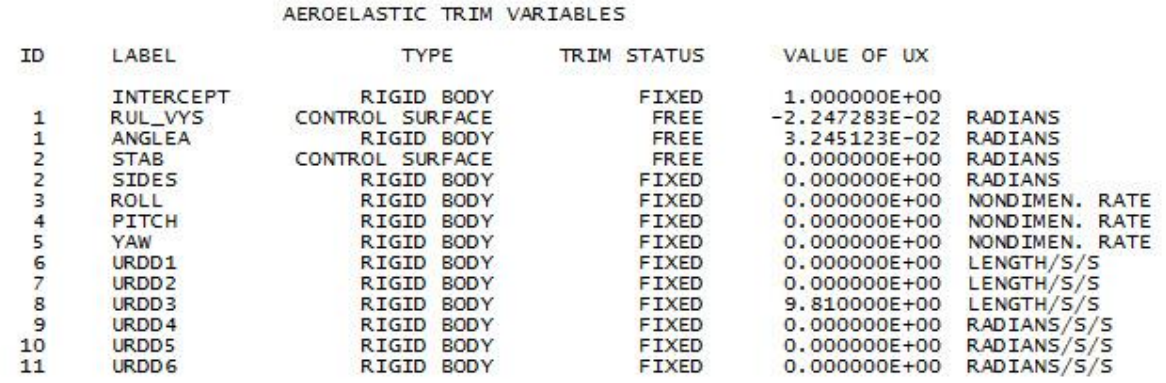


```
                              AEROELASTIC TRIM VARIABLES

   ID      LABEL                    TYPE         TRIM STATUS       VALUE OF UX

           INTERCEPT           RIGID BODY              FIXED      1.000000E+00
   50      ELEV_3D        CONTROL SURFACE               FREE     -6.794239E-03  RADIANS
  681      ANGLEA              RIGID BODY               FREE      2.013247E-02  RADIANS
  682      PITCH               RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
  683      URDD3               RIGID BODY              FIXED      9.810000E+00  LENGTH/S/S
  684      URDD5               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
```

Figure 6.3: Rigid Trim. Aeroelastic Trim Variables. Non-linear aerodynamics approach

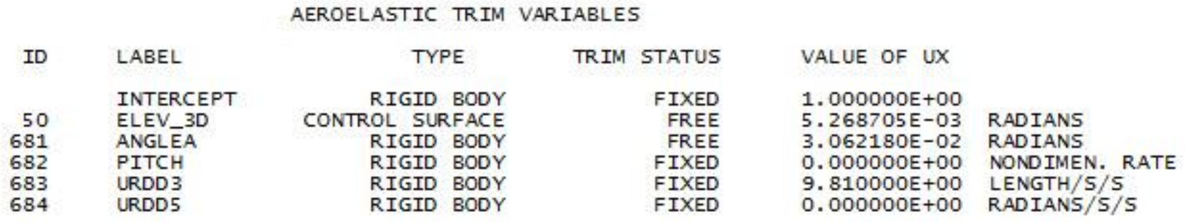


```
                              AEROELASTIC TRIM VARIABLES

   ID      LABEL                    TYPE         TRIM STATUS       VALUE OF UX

           INTERCEPT           RIGID BODY              FIXED      1.000000E+00
    1      RUL_VYS        CONTROL SURFACE               FREE     -2.247283E-02  RADIANS
    1      ANGLEA              RIGID BODY               FREE      3.245123E-02  RADIANS
    2      STAB           CONTROL SURFACE               FREE      0.000000E+00  RADIANS
    2      SIDES               RIGID BODY              FIXED      0.000000E+00  RADIANS
    3      ROLL                RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
    4      PITCH               RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
    5      YAW                 RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
    6      URDD1               RIGID BODY              FIXED      0.000000E+00  LENGTH/S/S
    7      URDD2               RIGID BODY              FIXED      0.000000E+00  LENGTH/S/S
    8      URDD3               RIGID BODY              FIXED      9.810000E+00  LENGTH/S/S
    9      URDD4               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
   10      URDD5               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
   11      URDD6               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
```

Figure 6.4: Rigid Trim. Aeroelastic Trim Variables. Linear (DLM) aerodynamic approach



```
                              AEROELASTIC TRIM VARIABLES

   ID      LABEL                    TYPE         TRIM STATUS       VALUE OF UX

           INTERCEPT           RIGID BODY              FIXED      1.000000E+00
   50      ELEV_3D        CONTROL SURFACE               FREE      5.268705E-03  RADIANS
  681      ANGLEA              RIGID BODY               FREE      3.062180E-02  RADIANS
  682      PITCH               RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
  683      URDD3               RIGID BODY              FIXED      9.810000E+00  LENGTH/S/S
  684      URDD5               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
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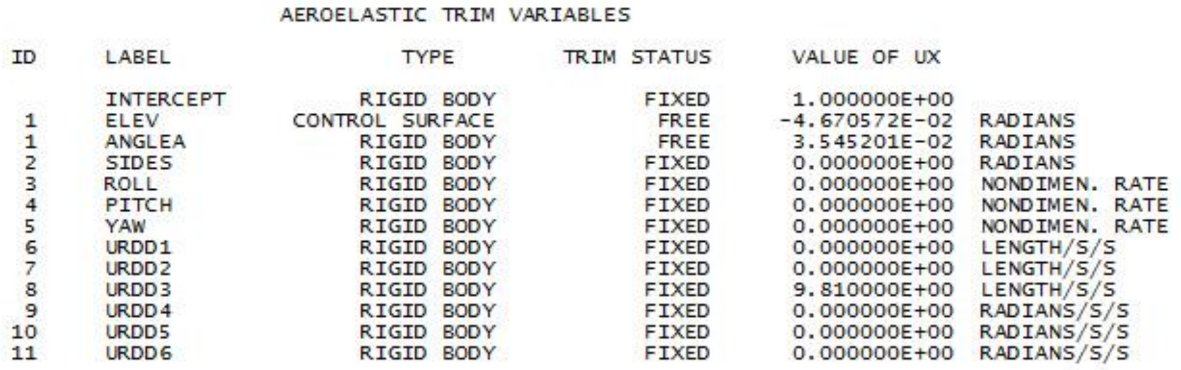
Figure 6.5: Flexible Trim. Aeroelastic Trim Variables. Hybrid (CFD+DLM) aerodynamic approach



```
                              AEROELASTIC TRIM VARIABLES

   ID      LABEL                    TYPE         TRIM STATUS       VALUE OF UX

           INTERCEPT           RIGID BODY              FIXED      1.000000E+00
    1      ELEV           CONTROL SURFACE               FREE     -4.670572E-02  RADIANS
    1      ANGLEA              RIGID BODY               FREE      3.545201E-02  RADIANS
    2      SIDES               RIGID BODY              FIXED      0.000000E+00  RADIANS
    3      ROLL                RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
    4      PITCH               RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
    5      YAW                 RIGID BODY              FIXED      0.000000E+00  NONDIMEN. RATE
    6      URDD1               RIGID BODY              FIXED      0.000000E+00  LENGTH/S/S
    7      URDD2               RIGID BODY              FIXED      0.000000E+00  LENGTH/S/S
    8      URDD3               RIGID BODY              FIXED      9.810000E+00  LENGTH/S/S
    9      URDD4               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
   10      URDD5               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
   11      URDD6               RIGID BODY              FIXED      0.000000E+00  RADIANS/S/S
```

Figure 6.6: Flexible Trim. Aeroelastic Trim Variables. Linear (DLM) aerodynamic approach

Comparison of the results using the DLM approach and the hybrid (CFD+DLM) approach shows that:

- Trim solution evaluated by using CFD data forces lead to a value of the angle of attack lower that one given by DLM approach.
- Static Aerodynamic effect due to airfoil geometry (camber, thickness) taken into tanks to the Rigid Aerodynamic database.

Finally, static deformations of the elastic airplane in level flight and the loads acting on the airframe units in trim level flight are concerned, shown in Figures 6.7-6.9.

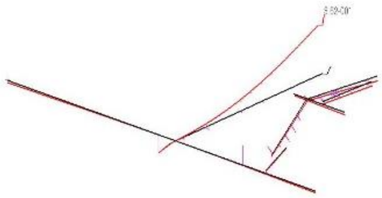


Figure 6.7: Structural model. Linear Deformations

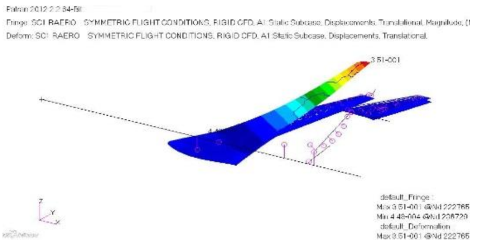


Figure 6.8: Aerodynamic model. Linear Deformations

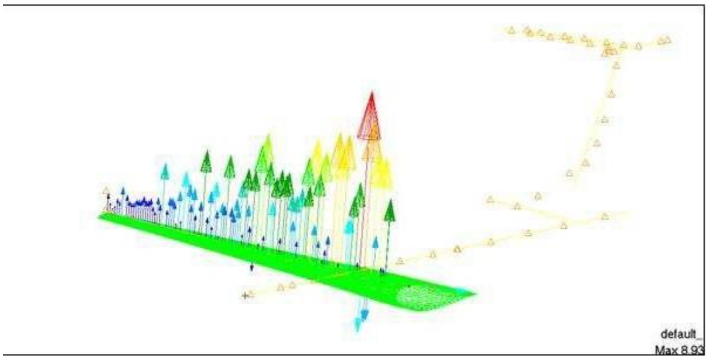


Figure 6.9: Aeroelastic force vectors

7 CONCLUSIONS

The results of the calculations are obtained for refined analysis of flight loads and trim parameters using the three-dimensional aerodynamic mesh.

The implemented solution method allows considering the rigging angles, thicknesses, camber and shape of the wing profile in aeroelasticity problems. The pressure center was calculated with more accuracy by such approach than by DLM one.

The results can be used in static strength analysis.

The next stage of the research involves the export in CFD codes the resulting deformed three-dimensional aerodynamic model to build new mesh and, further, to refine the aerodynamic loads.

Modern computer implementation of applied computational methods of solving aeroelasticity problems can significantly increase accuracy of the results.

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