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FAST ITERATIVE SIMULATION OF AIRLINER WING PLANFORM CONCEPTUAL DESIGN

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Abstract

This article illustrates the fast iterative simulation process of wing planform conceptual design. The whole process is built on simplified numerical simulation, based on validated CFD, FEM and CSD methods. There are three main data flow in this process: aerodynamics, weight and rigidity requirements. The variation of wing aspect ratio is investigated as example to show the multidisciplinary influence.

Keywords: multidisciplinary, iterative simulation, wing concept, airliner

1. The empirical method of wing planform conceptual design

Wing is the a core part of aircraft that supplies vast majority of lift, there are 5 important characteristic parameters of wing planform: reference area, aspect ratio, sweep angle, taper ratio and kink position. There are different definition of wing reference area, this article refers to the ESDU[1] definition. The definition of each parameter is illustrated in Figure 1 below.

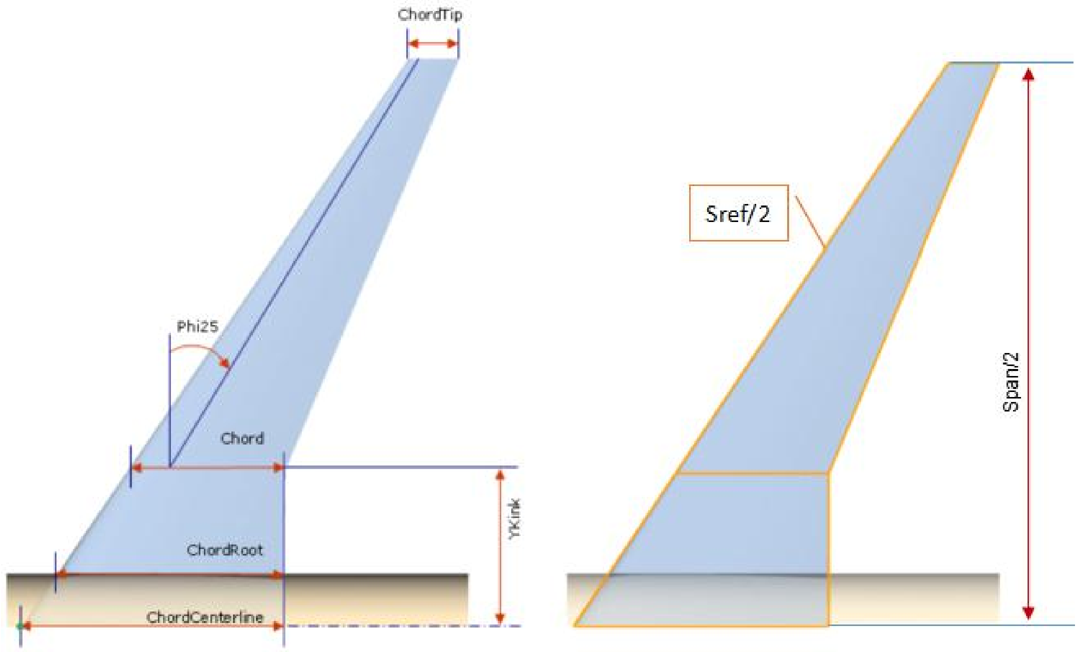

Figure 1 – Characteristic parameters of wing planform

Each parameter has apparent impact on wing structure weight and aerodynamic drag, thus has further impact on aircraft performance. In order to evaluate the impact from wing planform parameter to aircraft performance, the simple common way is to use empirical formula method, which is illustrated in airplane design book[2]. In those books there are many different sets of empirical formula system, such as wing structure weight shown below:

$$\frac{W_W}{W_{MZF}} = k_S b_S^{0.75}\left(1+\sqrt{\frac{b_{ref}}{b_s}}\right)\cdot n_{ult}^{0.55}\cdot\left(\frac{b_s/t_r}{W_{MZF}/S_{ref}}\right)^{0.30} \quad (1)$$

$$\frac{W_W}{W_{MTO}^{0.389}} = 19.938 S_{ref}^{0.843}(1+\cos\Lambda_{1/4})^{-1.017} AR^{0.192}\left(\frac{t}{c}\right)_{root}^{-0.098}\left(\frac{V_D}{100}\right)^{0.232}(1+K_{uc})^{0.407}(1+K_e)^{-1.159} \quad (2)$$

However, there are several apparent disadvantages of those formulas, first is that the accuracy can not satisfy the engineering requirement of aircraft design. Second, different formulas cause different variation trend with input parameter, which is difficult to justify which one is more reasonable. Formula 1 shows that the wing structure weight affected by W_{MZF}, i.e. maximum zero fuel weight, while Formula 2 shows that wing structure weight is affected by W_{MTO}, i.e. maximum take off weight. Third, the change rate with variation of input parameter such as aspect ratio is different, which may cause different compromised value between structure weight and aerodynamic drag. It is the similar case with aerodynamic estimation formula. In general, the empirical method can provide a good choice for theoretical concept design, but can't support the engineering requirement of current aircraft type development.

2. Simulation process of wing planform conceptual design

Determination of each parameter is a multidisciplinary process with many subjects such as aerodynamics, structure and stress, elastics and flutter, configuration and layout etc. To achieve the overall optimization, a lot of design iteration shall be made before freezing wing planform. Therefore the efficiency and quality of those iterations will determine the integrated performance and operating cost of aircraft. Generally, the fastest way of conceptual design iteration is based on engineering estimation methodology. And the current most accurate way is based on collaborative design cooperation between related subjects and professional teams. To make the best balance between efficiency and accuracy, simplified numerical simulation of multidisciplinary is a feasible and optimal way to achieve this target. This article aims to build the fast iterative process of airliner wing conceptual design and take wing aspect ratio as an example to illustrate period cycle and data flow of this process. The whole process is shown in Figure 2 below:

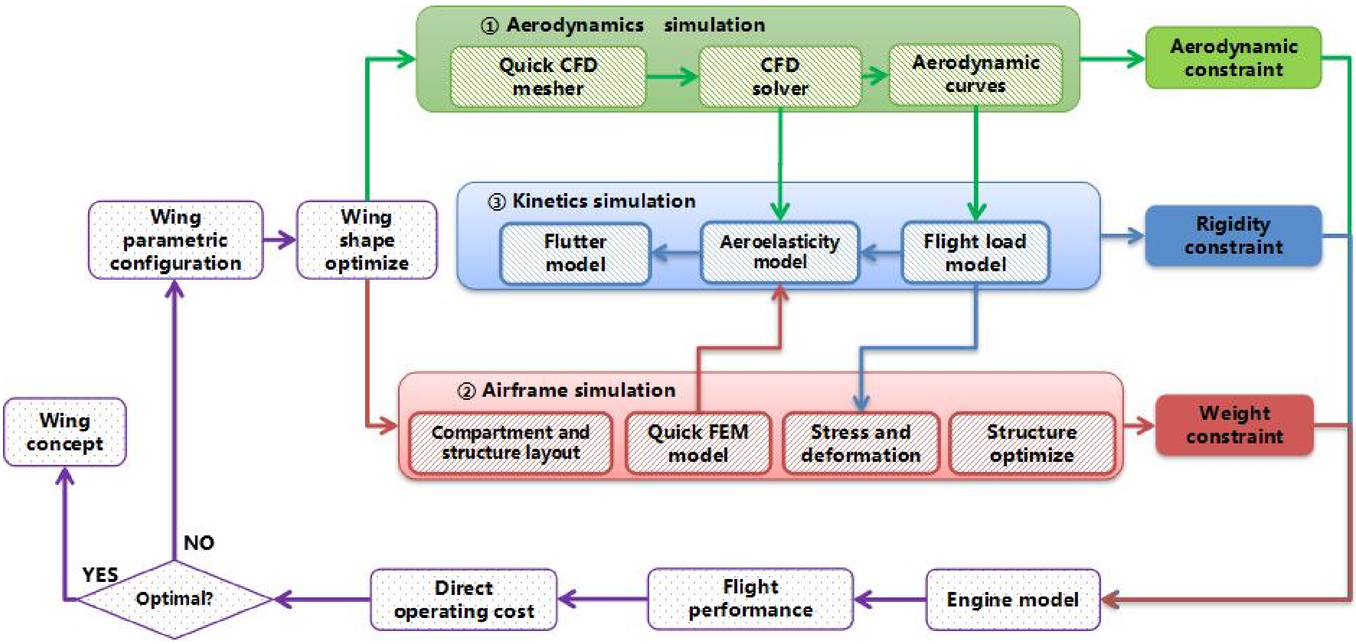

Figure 2 – Iterate simulation process of wing concept design

As shown in Figure 2, the iterative process begins with the wing configuration parametric definition model, followed by the wing aerodynamic shape optimization model. Based on the optimized aerodynamic shape, there are three main data flow of simulation, first is the aerodynamic simulation, second is the airframe simulation, third is the kinetics simulation. With simulation data satisfying the main constraints, the flight performance can be analyzed with given engine data. Finally the direct operating cost acts as the integrated index to find the optimal wing concept.

3. Simplified simulation of aerodynamic model

3.1 Introduction of aerodynamic model

The main concern of this aerodynamic simulation model is to study the influence from wing planform parameter to the aerodynamic performance of the aircraft. There are some simplification in this model: first the geometry of fuselage and empennages are all fixed. Second the airfoil shape and thickness span-wise distribution keep constant. A typical super-critical airfoil is introduced for modern commercial airliner study. Third, the aerodynamic fast simulation model is built based on conservative full-potential equation with correction of boundary layer viscid effect, which is a rational balance between time and accuracy.

In order to achieve an reasonable aerodynamic performance of wing, the twist angle span-wise distribution is optimized, the main objective is to have best cruise lift to drag ratio of the wing, second is to have lower wing root bending moment. The twist angle optimization model is built based on iSIGHT[3], which is shown in Figure 3. Inside this model, the wing twist angle curve is defined by a 5th order polynomial function in formula 3.

$$T = A\eta^5+B\eta^4+C\eta^3+D\eta^2+E\eta+F \quad (3)$$

The optimization model use NSGA-II genetic algorithm. The optimize variable is an array of polynomial coefficient. The polynomial function is introduced in order to keep the curve smooth.

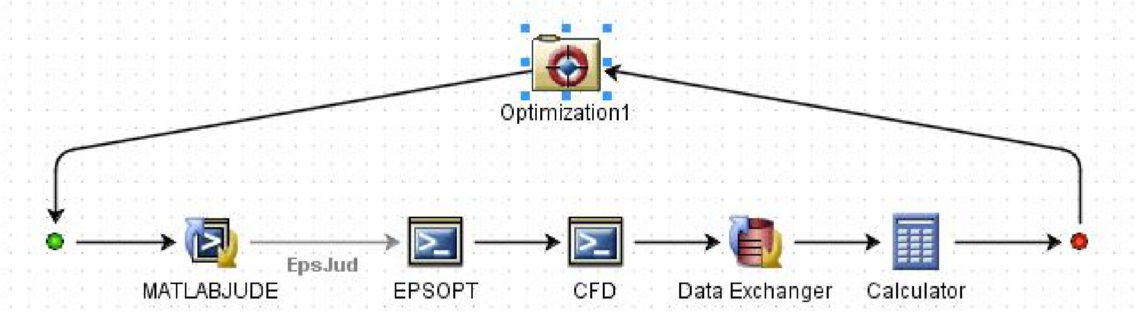

Figure 3 – Optimization model of wing twist angle distribution

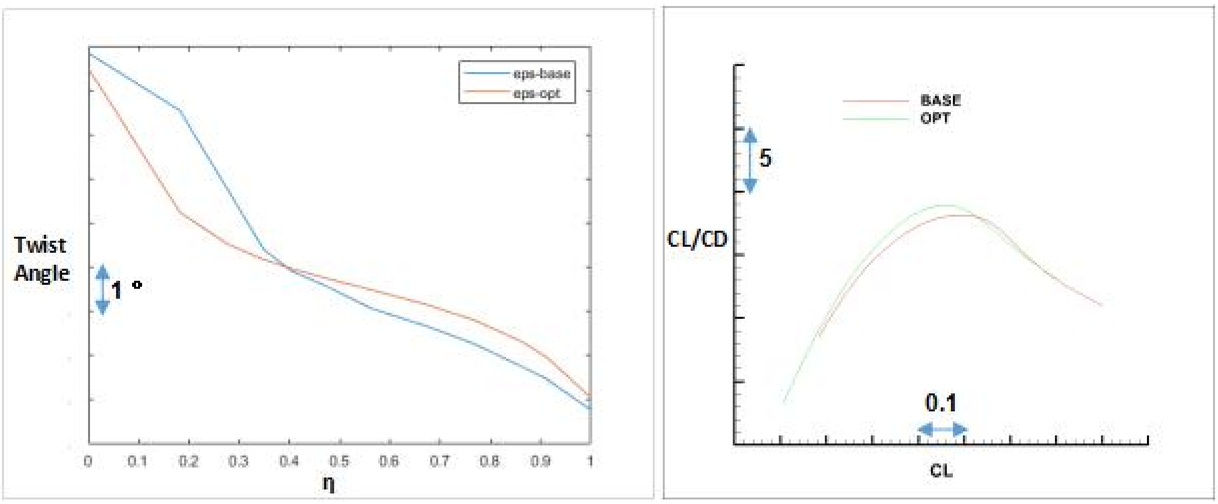

Figure 4 – Example of wing twist angle optimization model

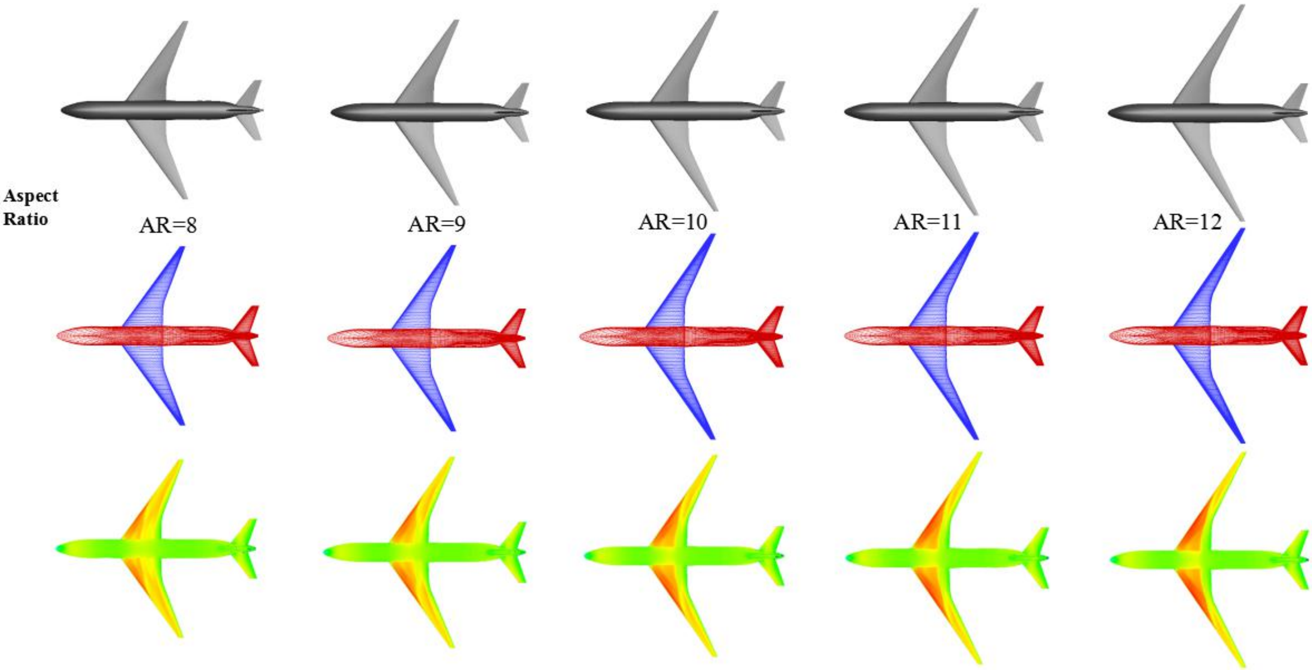

Figure 5 – Example of aerodynamic simulation of wing aspect ratio.

Wing aspect ratio is the most comprehensive index of wing planform parameter. In order to investigate the influence of aspect ratio, there are five wing concepts defined with different aspect ratio range from 8 to 12. the other parameters such as reference area and sweep angle all keep constant.

Figure 5 shows an example of the wing geometry, mesh model and static pressure contour with different aspect ratio, generated by the quick aerodynamic simulation model. There are different methods of quick aerodynamic simulation[4], while the most difficult point is to make it parametric and generate adaptive mesh model. As the input for aerodynamic simulation, there is a parametric geometry definition model and wing shape optimization model, focusing only on wing twist angle curve, while the airfoil is chosen and keep constant in this model. In order to increase the iterate efficiency of aerodynamic simulation, the process from parametric geometry model to wing shape optimization model and quick meshing model and CFD solver model all could be run automatically as needed.

3.2 Simulation results analysis of wing aspect ratio

The following three figures show the simulation results from wing aspect ratio to aerodynamic performance. Figure 6 shows the lift coefficient variation with angle of attack under different wing aspect ratio. Figure 7 shows the lift to drag ratio variation with lift coefficient. Figure 8 shows the pressure center relative span wise position with lift coefficient. Under the same lift coefficient, the pressure center span wise position can reflect the wing root bending moment.

Based on those three figures, the slope between lift coefficient and AOA is increased with wing aspect ratio, and also the maximum lift to drag ratio also increase with aspect ratio. The pressure center span wise location also increase with aspect ratio, which means the wing root bending moment increase with aspect ratio.

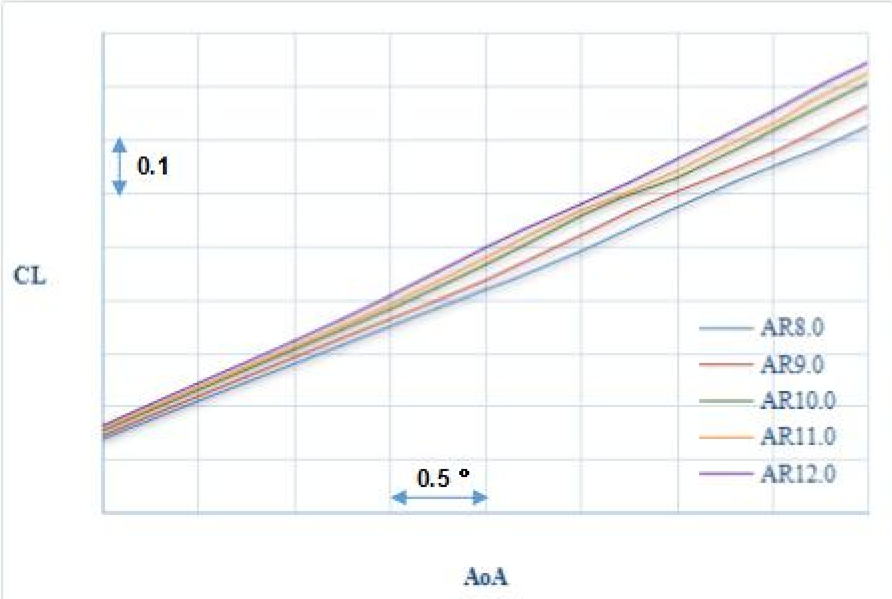

Figure 6 – CL vs AoA with different AR.

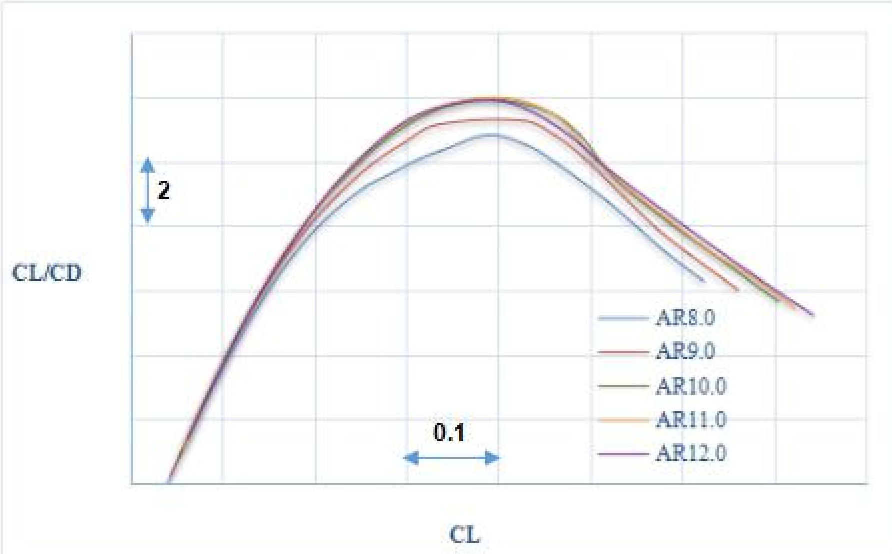

Figure 7 – Lift to drag ratio vs CL with different AR.

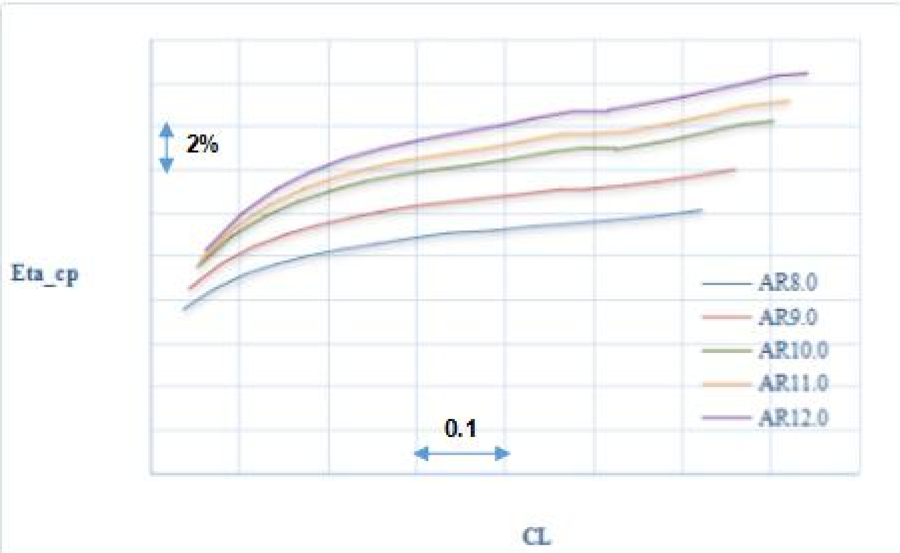

Figure 8 – Pressure center span wise position vs CL with different AR.

4. Simplified simulation of structure and stress model

4.1 Simulation process of wing airframe model

Compared with aerodynamic model, the numerical simulation of wing structure is much more complex. There are several main objectives of airframe simulation.first is to get the reasonable result of structure and mass distribution. Second is to study impact from input such wing plan form parameters. Third is to analyze the rigidity or aero elasticity effect of wing parameter. i.e. wing bending and rotation deformation, aileron elastic to rigid efficiency, wing flutter mode and speed. Figure 9 shows the simulation process of wing airframe model.

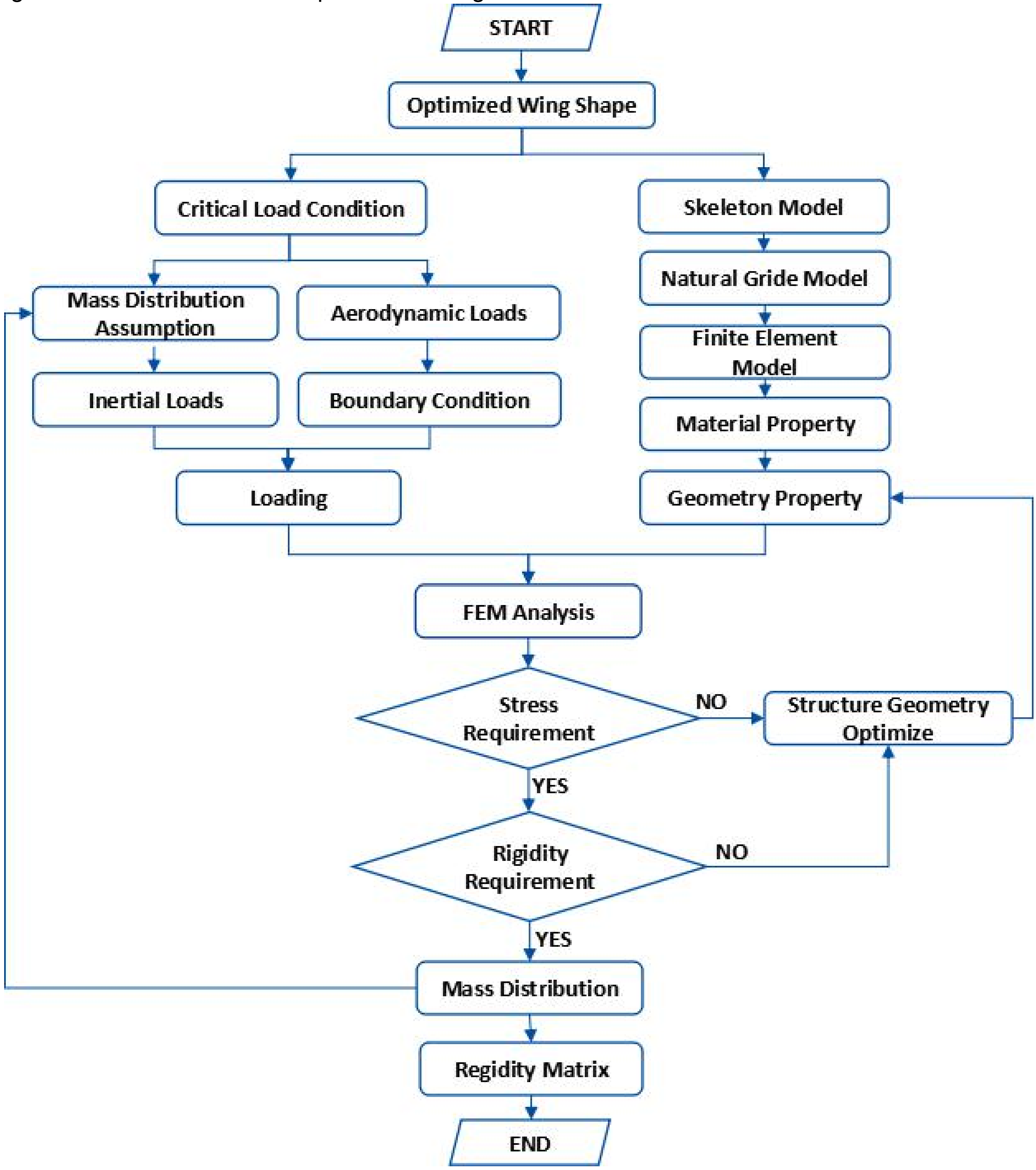

Figure 9 – Airframe simulation flow of wing aspect ratio

In order to reduce the difficulties of numerical simulation, the wing structure is simplified into the main structure of wing box in this model[5]. Because the wing box sustain majority part load and mass. The high lift device and control surface are neglected in simulation and compensated by multiplying correction coefficient after simulation.

As shown in Figure 9, the start point of this model is the optimized wing shape, which is output of aerodynamic optimization model, however the airframe simulation model is not sensible to twist optimization. Thus the twist optimization could be deactivated for airframe simulation to improve efficiency. Next step is the skeleton model which defines the main structure layout of wing box, such as front spar and rear spar, the reference positions of ribs and stringers. Then the natural grid model and finite element model define the grid and cell size and property, including the material property and local section geometry or thickness. Besides the FEM model, the critical load condition and correspondent aerodynamic and inertial loads are analyzed and calculated. With Loads and FEM model, first the stress requirement are iterated and satisfied, then the stiffness requirement are iterated and satisfied. The output is the mass distribution and rigidity distribution.

Figure 10 shows an example of the wing geometry, structure layout, mesh model, loading model and deflection contour. Wing structure geometry is optimized based on simulation results of stress and deformation, the first concern is the static stress, but the more critical constraint is static elasticity and flutter, which define the rigidity requirement. Finally the flight performance and operating cost model make balance between aerodynamics, rigidity and weight requirements, with the index of block fuel and operating cost of typical route. Generally speaking, wing aspect ratio around 10 will make best integrated performance of the transonic conventional configuration airliner, further increment will cause difficulties in structure and equipment layout, and dramatically increased rigidity requirement due to flutter and aileron efficiency.

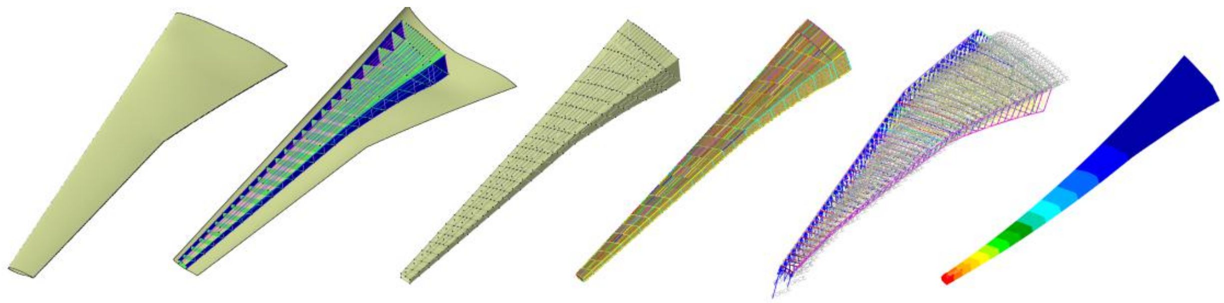

Figure 10 – Airframe simulation flow of wing aspect ratio

The stress requirement is decided by material property and safety factors. However, the rigidity requirement is much more complex to determine, and in most cases, the rigidity requirement is more difficult to fulfill, thus act as the critical requirement to impact the structure weight. Normally the rigidity requirement is decided by flutter speed and static aero elasticity as aileron efficiency. Figure 11 shows an example of simplified flutter model consist of FEM model and simplified CFD model. There are different selection of rapid flutter analysis method[6], the key point is to find out the most suitable way for your own project. During the fast simulation of flutter, the liner aerodynamic model could be used and calibrated by a few nonlinear CSD model.

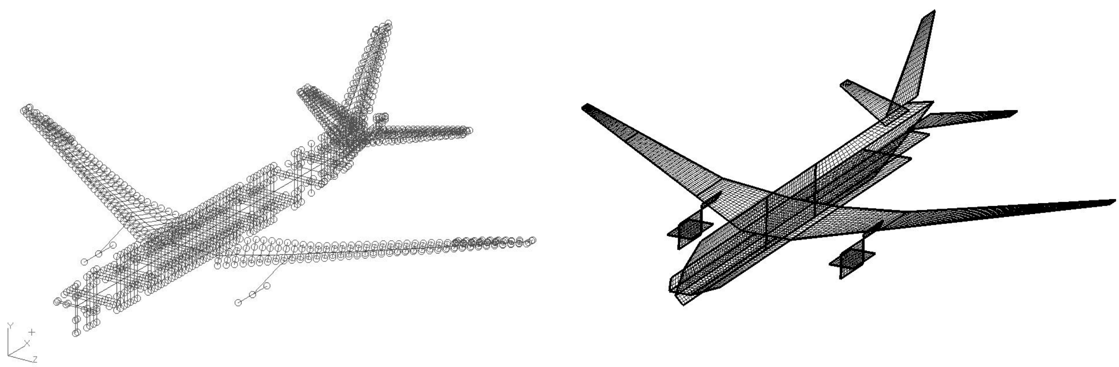

Figure 11 – Simplified flutter analysis model

5. Performance simulation and operating cost analysis

Through aerodynamic simulation model and airframe simulation model, the impact from wing planform parameter to drag polar and structure weight could be generated and analyzed and. The fast iterative simulation model could overcome the disadvantage of empirical formula methods and simulate numerically the influence of characteristic weight, structure layout, velocity envelope and so on. The increased wing aspect ratio make higher cruising lift to drag ratio and heavier wing structure weight, in order to balance the two contradictory effect, this paper introduce a flight performance model in Pacelab APD[7] and use typical route block fuel or direct operating cost as the integrated index to evaluate total influence. Figure 12 shows the flight profile to calculate the block fuel of typical route.

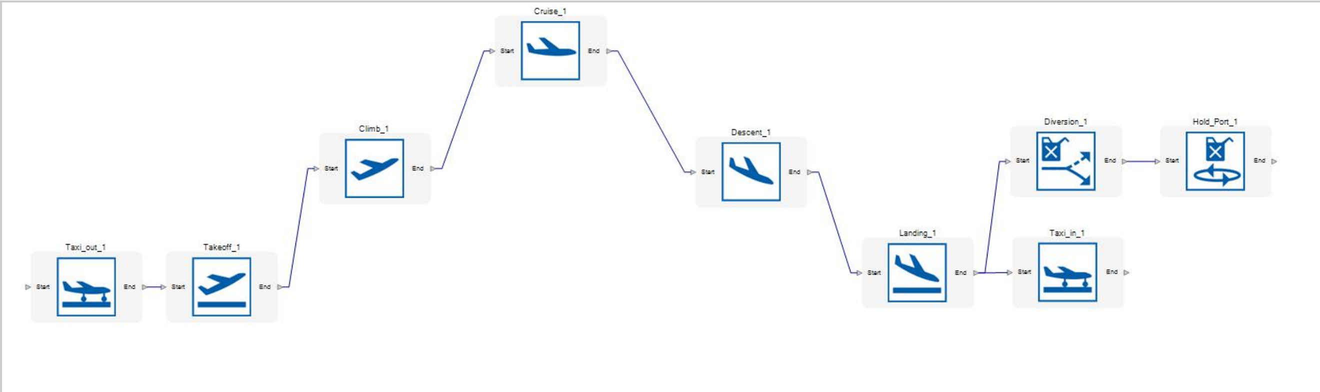

Figure 12 – Flight profile definition of typical route of airliner

6. Summary

After the fast numerical simulation model was built and calibrated, the impact from wing aspect ratio to aircraft concept could be trade-studied and iterated. The primary objective is to illustrated the whole iterate procedure, the methodology and the simplification assumption of different simulation model. Thus the detailed data were all not presented in this article. However there are several conclusions could be gained based on the iterated data of aerodynamic and structure and stress as following:

- The current advanced airliner with high transonic cruise mach number take wing with aspect ratio around 10;
- When aspect ratio smaller than 10, the reduced induced drag could overweight the increased structure weight, thus higher the increased aspect ratio could have reduced block fuel and lower operating cost as a result;
- When aspect ratio bigger than 10, further increase with wing aspect ratio could cause much higher structure weight as a much narrower wing box structure to sustain a increased rigidity requirement due to flutter and aileron efficiency, which cause bigger block fuel and operating cost.

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