Computer Aided Design and Analysis of Context-Aware Axial Flow Compressors

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Abstract: This paper explains process of defining suitable design/analysis methods for context-aware axial flow compressor and using them to develop exclusive software to design and model gas turbine engines with this type of compressors. To approach the aim, conventional design method was converted into an object-oriented system and defined by UML. This system was afterward used to define an object-oriented system to design context-aware axial flow compressors. Finally resulted system was used as a base to develop exclusive software to design and model such compressors.

Keywords: UML, object-oriented system, design, off-design operation, axial flow compressor, characteristic map, computer modeling, context-awareness;

Nomenclatures

C	Air Velocity-also-Coefficient
c	Chord
IR	Increment of Hub-tip Ratio Stage by Stage
i	Incidence Angle
K	Coefficient to determine taper of blades
m	Air Mass Flow Rate
N	Rotational Speed

P Pressure

R Radius Ratio

r Blades Radius

s Blades Pitch or Space

T Temperature

U Rotor Blades Velocity

V Air Relative Velocity to Blade

α Angle between Air Approaching Velocity and Axial Velocity

β Angle between Air Relative Velocity and axial Velocity

δ Angle between air vector mean velocity and air axial velocity

η Efficiency

Λ Degree of Reaction

$\Delta\theta$ Air Turning Angle

θ Blades Camber Angle

ρ Density

σ Centrifugal Stress

ζ Cascade Stagger Angle

Abbreviations

IT Information Technology

ICCSE Interaction of Context-aware Compressor/fan with System Evaluator

NASA National Aeronautics and Space Administration

APNASA Average-Passage flow code of NASA

NPSS Numerical Propulsion System Simulation

STGSTK 1D mean line stage-stacking program

UML Unified Modeling Language

Units

kg Kilogram

m Meter

s second

Suffix

0 Stagnation State

1 Inlet to Compressor- also –Inlet to Rotor

2 Inlet to Combustor- also –Exit from Rotor

3 Exit from Stator

a Axial

b Blades

C Compressor

ct Critical

D Total Drag

i Stage Number

m Mean Radius

R Relative to design value

r Root Radius – also – Radial Component

S Stage

t Tip Radius

w Whirl Component

1. Introduction

Although concept of context-awareness has been formed in the IT world, and thus, inherently has been constructed for computer technology **[1]**, however it has high potential to use in gas turbine engines. These engines are designed to use by different users in different environment. This major point needs adaptation ability to environmental elements and user demands, which is simple definition of context-awareness.

To raise a gas turbine engine up to a context-aware system, author considered enhancing capability of free access to components to manage them individually. This view urges making essential changes in compressor operation and power transmission. In fact, coherent consistency should replace conventional strong link among the components, which allows all effective components of all sections to be capable to tune toward environmental elements and user demands independently and consistently.

Accordingly, author considered such changes for axial flow compressor and modeled that by computer **[2]**. In the study, it is assumed that compressor's stages are able to receive needful energy individually and convert that independently, and thus they are capable to adapt themselves to environmental elements and user demands by changing rotational speed.

Because of completely different entity of this type of compressor operation, conventional design and analysis methods are not competent, and then new and proficient methods are needed to form and represent performance of the compressor. On the other hand, capability of methods to convert to computer code is crucial. This urges accurate procedures to organize design and analysis steps while proper parameters to define suitable formulations are essential to gain the target. Accordingly, a general design method was selected and defined as object-oriented system, and then, converted to UML from which a suitable design system for axial flow compressors with individual rotor rotational speed for each stage was derived. This process was selected for three essential reasons:

1. Creating suitable design system for such compressors needs exact analyze of system requirements and one of the best techniques is application of object-oriented analysis **[3]**.
2. Today computer simulation is a powerful and reliable tool to model and analyze gas turbine engines, and object-oriented technology is a base to develop particular object-oriented software in this field **[6]**.
3. To develop exclusive object-oriented software for this project, a standard model of object-oriented system was needed, so UML as standard language to generate standard object-oriented model of software was the best catalyst **[5]**.

This article summarily explains the process of developing suitable software to model context-aware axial flow compressor. In this way, first, derivation of design method for axial flow compressor with individual rotor rotational speed in each stage is explained, and next, exclusive software developed for this project is introduced.

2. Modeling and deriving desirable system

In the first step, a general method commonly used for designing axial flow compressors was selected, and then it was used to derive desirable process.

2.1 Modeling design system of conventional compressors

First pace is to define an object-oriented process on the basis of this general design method, as a result the method suggested by **[6]** was considered. This design process has three major sections: first defining overall characteristic of compressor, second, stage-by-stage design and third, performance sizing by drawing compressor characteristic map, however, cycle optimization should be done before starting the process. These three sections contain following steps:

I. Choosing rotational speed and annulus dimensions;
II. Determining number of stages, using an assumed efficiency;
III. Calculating the air angles for each stage at the intended radius;

IV. Determining the variation of the air angles from root to tip;

V. Investigating compressibility effects;

VI. Selecting compressor blading, using the experimentally obtained cascade data;

VII. Checking on efficiency previously assumed, using the cascade data;

VIII. Estimating off-design performance;

IX. Rig testing;

Items II and I relate to first section, second section encompasses cases III through VII and finally items VIII and IX relate to third section. To model a system, first phase is problem definition indicating user exceptions. Considering designer is user of system, framework of user exceptions is foregoing sections. Hence, they can be collected as follow:

- Cycle optimizing
- Designing an axial flow compressor to deliver desirable pressure ratio by rational number of stages. The design should be able to service in intended thermodynamic cycle by using given airflow at design point.
- Performance sizing of the compressor at arbitrary off-design conditions
- Providing all needful aerodynamic and thermodynamic details for each stage at design point and off-design condition

Software structure is formed compatible with aforementioned functionalities and design / analyze method. To start system formation process, its static structure indicating its object-orientation was drawn in the class diagram **Fig.1**. By regard to this fact that some parameters such as inlet axial velocity should be available in all classes, inheritance is an important and inevitable property to shape system. On the other hand utilizing polymorphism to calculate changes of temperature will be useful, because it provides feasibility of different responses to same messages for classes **[7]**. **Table.1** indicates responsibilities and collaborations of classes.

In the next step to illustrate system dynamic aspect, drawing use-case diagram is helpful, because it simplifies analysis of system. **Fig.2** indicates this diagram having three actors: *Calculation Unit*, *UI* and *Designer*.

Herein *Designer* is symbol of system user, *Calculation Unit* carries out calculations and *UI*, a generalization for other actors, is symbol of user interface. Two use-cases, *Design Point Characteristic* and *Optional Characteristic*, provide inputs of *Designer* in the system. *Design Point Characteristic* is responsible for inputting design point characteristic and *Optional Characteristic* is responsible for inputting characteristics that should be either selected or changed to gain better results. Analyzing outcomes, for that *Analyze Outputs* is responsible, assesses requirement of changes. *UI* transfers *Designer* inputs to *Calculation Unit* via *Inputs* and another responsibility of that is to warn user about critical values such as pressure and shock losses via *Control Critical Values*. In fact, it functions like the expert system. Finally, *Calculation Unit* carries out all calculations necessary in the systems via *Rotational Speed & Hub-tip ratio*, *Stage Number* and *Stage-by-Stage Design* use-cases.

2.2 Derivation of desirable system

Context-aware compressor has a major difference from conventional type, which is individual rotational speed in each stage. This specification urges defining limitations to set speed in stages; hence, rotational speed of each stage is set during stage design. In a word, in this type some basic characteristics are defined before starting stage-by-stage design, afterward, stages are individually designed based on them. Conventionally temperature rise of each stage is estimated first, and then by considering a constant rotational speed, compressor is designed stage by stage successively. Nevertheless, in the intended type of compressor, each stage has an individual rotational speed; hence, when design process of each stage is begun temperature rise is also estimated. Rotational speed of each stage is obtained individually for optimum and maximum allowable value, which is measured compatible with flow and critical centrifugal stress conditions. As a result, number of stages to achieve desirable overall pressure ratio, will not be cleared before end of the compressor design process.

To derive class diagram for intended type of compressor, first similar diagram drawn for conventional compressor was considered, then, compatible with differences, classes that should be removed or added were determined. *Rotational Speed & Annulus Dimension* and *Stage number* were classes that should be removed and *Basic Characteristic* was the class added instead (**Fig.3** and **Table.2**).

In the Use-case diagram, although actors have responsibilities like pervious system, however, *Designer* uses two other use-cases, *Compressor Characteristic* and *Stage Characteristic*, that first one is to input basic characteristic of compressor and the other, is responsible for inputting each stage characteristic. *Stage Characteristic* provides proper conditions to design stages singly. *Calculation Unit* has only one use-case responsible for all necessary calculations in the system. Other sections have responsibilities like the pervious system. **Fig.4** shows this diagram.

In addition to design and analysis methods, to measure parameters like flow conditions in subsonic and supersonic regions and structural limitations, introducing suitable methods were crucial. Further more, defining these factors which represent environmental elements and user demands as specific classes in the programming structure needed particular methods. For more detail see **[2]**.

3. The software specifications

The software capable to satisfy the current project requirements should be able to optimize cycle, design three major sections of gas turbine engines, namely fan, compressor and turbine and model their behaviors at off-design conditions. The intended level to analyze is higher than low-fidelity like that is carried out by STGSTK **[8]**. However, to avoid high computing cost, high-fidelity analysis like the analysis done by NPSS and APNASA **[9, 10]**, is not suitable in this step. As a result, compressor, fan and turbine are designed and modeled in the foregoing level, named as average-fidelity level. Other sections such as combustor, nozzle, intake and duct are designed and simulated in the low-fidelity level.

3.1 Design and simulation tool

ICCSE: Interaction of Context-aware Compressor/fan with System Evaluator is object-oriented software developed by Visual C++ to design gas turbine engine with context-aware compressor/fan, model its behavior in the arbitrary off-design condition and analyze results. It means that compressor and fan are considered with individual rotor rotational speed in each stage capable to tune toward environmental elements and user demands. This integrated system provides the graphical user interface and operating environment for construction of arbitrary engine configurations, selecting and controlling steady state and transient engine operation, and graphical display of simulation results.

Data flow of software simulates flow through all the engine components, which is indicated in the **Fig.5**. **Fig.6** illustrates system schematic for a turbofan cycle; obviously such figure for a turbojet cycle has not components such as fan and duct. This figure shows data flow network for design process in which data is stored, and then, during simulation process, storage data is recalled and engine modeling is carried out.

3.2. Methodology of designing and modeling in ICCSE

Particular design method in this study should support selecting optimum rotational speed for each stage individually, which affects calculations and procedures.

3.2.1. Design

To start design process, designer should define some compressor specifications:

A. First stage's hub-tip ratio.

B. Value of increment of hub-tip ratio stage by stage (IR).

C. The safe blades tip speed for first stage to determine maximum allowable ratio.

D. Blading type, to determine velocities distribution along the blades.

E. Annulus shape to form blading.

In the average-fidelity level analysis, velocities along the rotors and stators blades are considered three dimensional, similar to method used by **[6]** in which whirl velocities and degree of reactions are defined as follow:

$C_{w1} = aR^n - \frac{b}{R}$ and $C_{w2} = aR^n + \frac{b}{R}$ **(1)**

where *"n"*, "*a*" and "*b*" are constant and "*R*" is the radius ratio $r/r_{m \text{ or } t}$. Degree of reaction can be written as

$\Lambda = 1 - \frac{C_{w2} + C_{w1}}{U}$ **(2)**

and the blades speed is given by

$U = U_{m \text{ or } t} R$ **(3)**

immediately seen that

$\left(C_{w2} - C_{w1}\right) = 2b/R$ **(4)**

By taking three values for *"n"* three types for velocities and distribution of degree of reactions (bladings) are obtained. More details of this analysis can be seen in **[6]** and similar textbooks.

In this study, for defining annulus shape two major types were selected:

1. Constant outer diameter in which $C_{a\,t} = \text{constant}$ and $U_{t1} = U_{t2}$
2. Constant mean diameter in which $C_{a\,m} = \text{constant}$ and $U_{m1} = U_{m2}$

Defining annulus shape is precondition to determine velocities' triangles. Usually three main radiuses are taken to calculate these triangles, namely root, mean and tip. Method and formulation to calculate these triangles can be found in the **[6, 11]** or other similar textbooks.

At the first point of designing each stage, designer should determine following characteristics **[6]**:

1. Degree of reaction (at mean or tip radius, depending on annulus shape)

2. Stage temperature rise
3. Blades aspect ratio
4. Blades tapered coefficient (K)
5. Ratio of the point of maximum camber

These characteristics are used to calculate geometrical and aerothermodynamic specifications in the three major aforementioned radiuses; however, they relatively change during calculations.

Besides major radiuses, all stages' specifications are calculated at two major locations: at entrance and exit of rotor. For instance in constant-outer-diameter design, root and mean radiuses at rotors' entrance differ from that of their exit.

Following relation is set to calculate r_r at entrance:

$$r_{r1} = \left(r_r / r_t \right) r_t \quad \textbf{(5)}$$

Therefore, r_r at rotors' exit is:

$$r_{r2} = r_t \left(IR/2 + r_r / r_t \right) \quad \textbf{(6)}$$

Compatible with root radiuses, mean radiuses are:

$$r_{m2} = \left(r_{r2} + r_t \right) / 2 \quad \textbf{(7)}$$

In constant-mean-diameter design, mean radius is considered constant and similar process is carried out to obtain root and tip radiuses.

Aforementioned specifications open the door to calculate more sophisticated characteristic of the stage. Absolute performance of the stage is taken at mean radius, but all characteristics are calculated at three major radiuses.

Following characteristics are calculated orderly to determine more accurate stage performance **[6]**:

1. *Velocities triangles*. By regard to this fact that defining the best specifications for the best performance is a principle to design cascades, in order to determine inlet angles to rotors, deflection angles of the stators

are considered for generating minimum possible stagnation pressure loss. Accordingly, the software sets the stator deflection ($\alpha_2 - \alpha_3$) to 30 degree in all stages but first stage.

2. *Stage rotational speed*. To set this speed, structural limitation is the most important criteria.
3. *Mach number at rotors' tip and stators' hub*. If flow Mach number indicates high risk of separation necessity of redesign is warned to designer. In addition, this parameter restricts rotational speed.
4. *Stagnation pressure loss*. Overall stagnation pressure loss is calculated as follow: $\textit{Overall Loss} = \Lambda \times \textit{Rotor Loss} + (1 - \Lambda) \times \textit{Stator Loss}$ .Designer is able to set the loss in the acceptable range when software indicates its value. This parameter, which is third factor to restrict rotational speed, is measured at mean radius.
5. *Stage temperature rise (stagnation and static)*. This specification is recalculated according to more precise characteristic of stage obtained up to now.
6. *Rotor and stator blades pitch/chord ratio, pitch, chord and number of those*. In order to clear geometrical specification of stage, incidence, stagger, camber, deviation, inlet and outlet angles are calculated. Sources of theses calculations are velocities' triangles solved by software and geometrical specification defined by designer.
7. *Lift and drag coefficients*. Tree major drag coefficients are considered in this study: profile drag, secondary loss and annulus drag, whose summation determines total drag coefficient.
8. *Efficiency of the blades row (η_b)*.
9. *Stage efficiency*.
10. *Stage stagnation and static pressure ratios*.

3.2.2. Modeling

In this study, showing capability of the system to face any operating condition is the most crucial aim. Therefore, compressor modeling was selected to impose arbitrary off-design condition on the compressor components and modeling their behaviors. Arbitrary off-design condition defines new environmental elements causing specific performance in the compressor, which is known as its behavior. Specifications defined during design process and saved as data identify each component.

3.2.2.1. Identifying the design

Design contains overall characteristic of compressor predefined by designer in the design start point, dimensional characteristic of stages and item 6 in the orderly design of stage explained in the section 3.2.1.

Other items of orderly design process are also followed here to calculate aerothermodynamic characteristic of stages. However, to calculate air exit angle of each stage's stator, method used in design process is not functional (item 1). In fact, cascades' specifications have already determined in the design and they must remain same in the off-design conditions. In this case, the point mentioned by **[12]** was considered. This reference's cascades data has suggested that air exit angles, namely β_2 for rotor and α_3 for stator do not change appreciably for a range of incidence up to the stall point. By some simplifications, for a given stage it can be inferred that:

$$\tan\alpha_3 + \tan\beta_2 = \text{constant} \quad \textbf{(8)}$$

It is assumed that Eq.8 governs flow around the stators before the stall bounds. Thereby its values could be calculated and recorded during design process for all stages, and then α_3 of each stage in the arbitrary off-design conditions can be estimated by using recorded value of Eq.8 and β_2 of pervious stage.

Because of individual speed in each stage, this assumption can be implemented reasonably. This specification allows preventing flow separation, so that stage would be kept outside the stall margin.

3.2.2.2. Modeling the design operation

Conventionally, rotational speed has been used to classify compressors characteristic maps. However, using this speed to illustrate overall performance of intended type is obviously insignificant.

Clearly, particular bound for this type should indicate the limit beyond that changing rotational speed could not help flow separation. Intended type of compressor's stages may confront with flow separation when $\alpha_1 + \beta_1$ overruns specific limits and then inlet axial velocity has crucial role to lead stages into surge margin.

As a result, new dimensionless parameter $\left.\frac{C_a}{\sqrt{T_1}}\right|_R$ which represents effects of this key parameter was defined by author to analyze compressor characteristic. Nevertheless, author considered summation of stages rotational speed per square root of its inlet stagnation temperature relative to design value, namely $\sum\left(\frac{N_i}{\sqrt{T_{0i}}}\right)_R$, to show effects of stages rotational speeds on off-design operations.

To facilitate assortment of results, effect of rotational speed regulation on this ratio is ignored.

ICCSE uses two ways to form off-design condition. One by defining a point by new air inlet axial velocity, rotational speed and altitude based on percentage of their design value, and the other by defining an off-design condition envelope formed by changing altitudes, $\left.\frac{C_a}{\sqrt{T_1}}\right|_R$ and $\sum\left(\frac{N_i}{\sqrt{T_{0i}}}\right)_R$ in a wide range. In all methods, each point is imposed on the compressor from first stages singly.

When new environmental elements formed by off-design condition moves each compressor stage into surge margin, ICCSE attempts to exit stage from this by changing the rotational speed; if it cannot return stage to safe situation this off-design condition is not classified as a point of compressor working envelop. The points detected as members of compressor working envelope form its characteristic map together. Mechanism to regulate rotational speed is tabulated in **Table.3**. Note deflection is $\alpha_2 - \alpha_3$ for stator and $\beta_1 - \beta_2$ for rotor. An example of ICCSE performance can be found in **[2]**.

4. Conclusion

Toward a study to raise axial flow compressors up to context-aware system exclusive software was developed to design and model behavior of such compressors. This procedure needs proficient design and analysis method capable to satisfy new requirements besides providing proper organization to convert process to computer code.

Accordingly, an object-oriented design system for this type was provided by using UML, and then, this system was utilized to develop exclusive software, ICCSE, to design, simulate and analyze gas turbine engines using context-aware compressor. The process of developing suitable design/analysis methods and using that for computer programming indicates effects of utilizing proper devices to change old methods toward requirements of novel designs.

However, one point remains open that is to define a specific standard for developing such methods by regard to already available methods, which need to be improved toward new requirements. As the computer molding is a common tool to evaluate novel ideas, such a standard is necessary for design.

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Figures

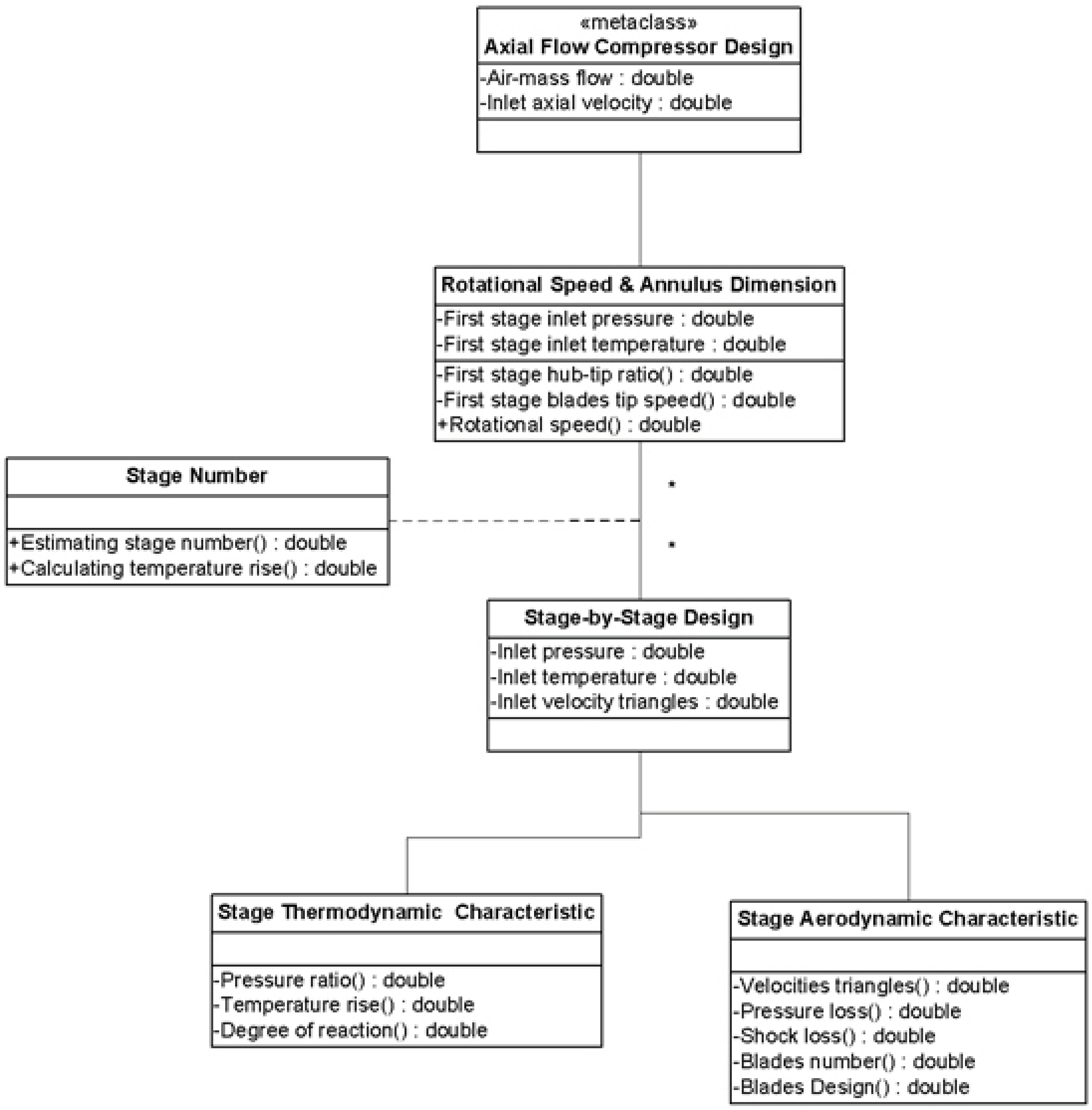

Figure 1: Class diagram for design system of conventional axial flow compressor.

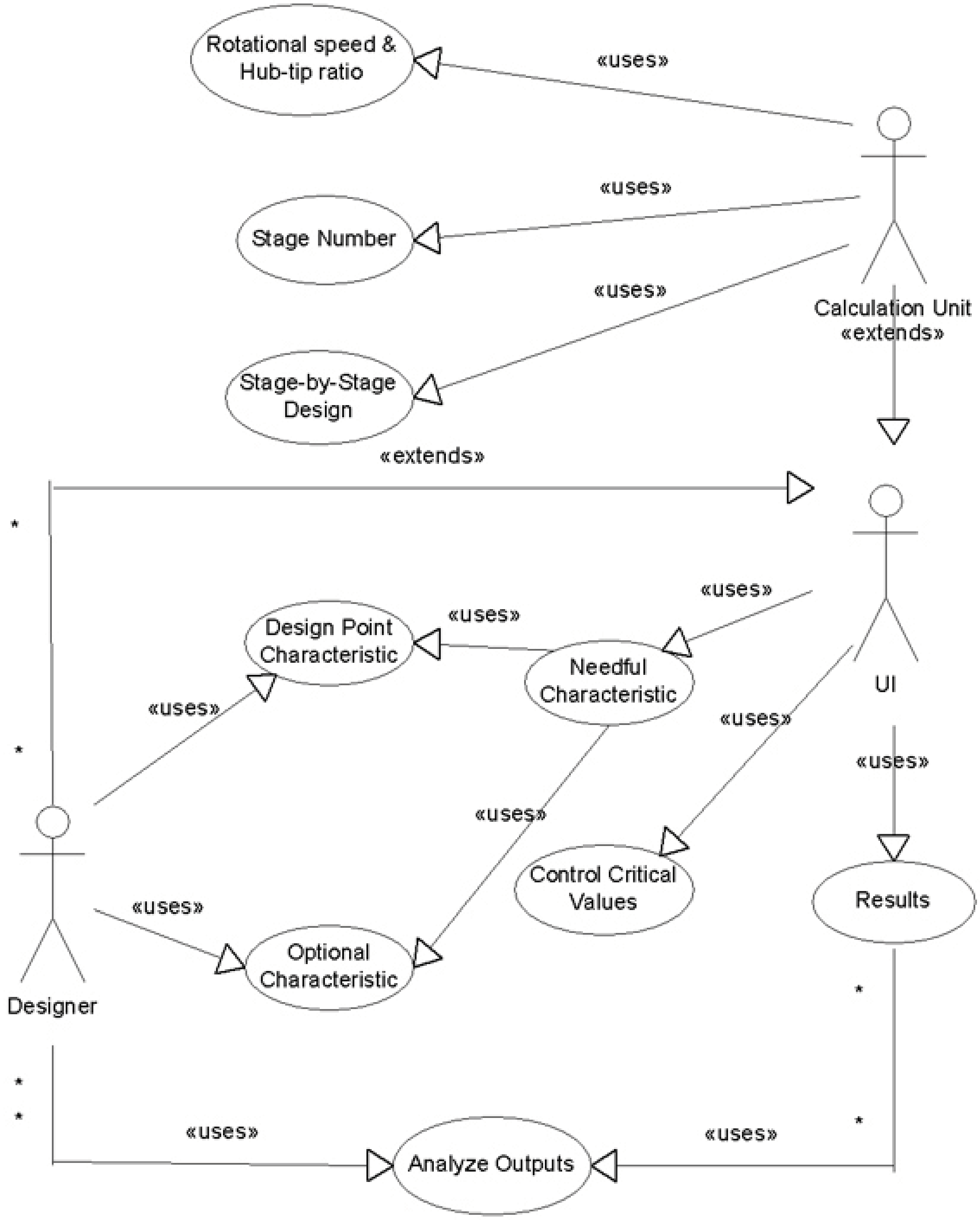

Figure 2: Use-case diagram for design system of conventional axial flow compressor.

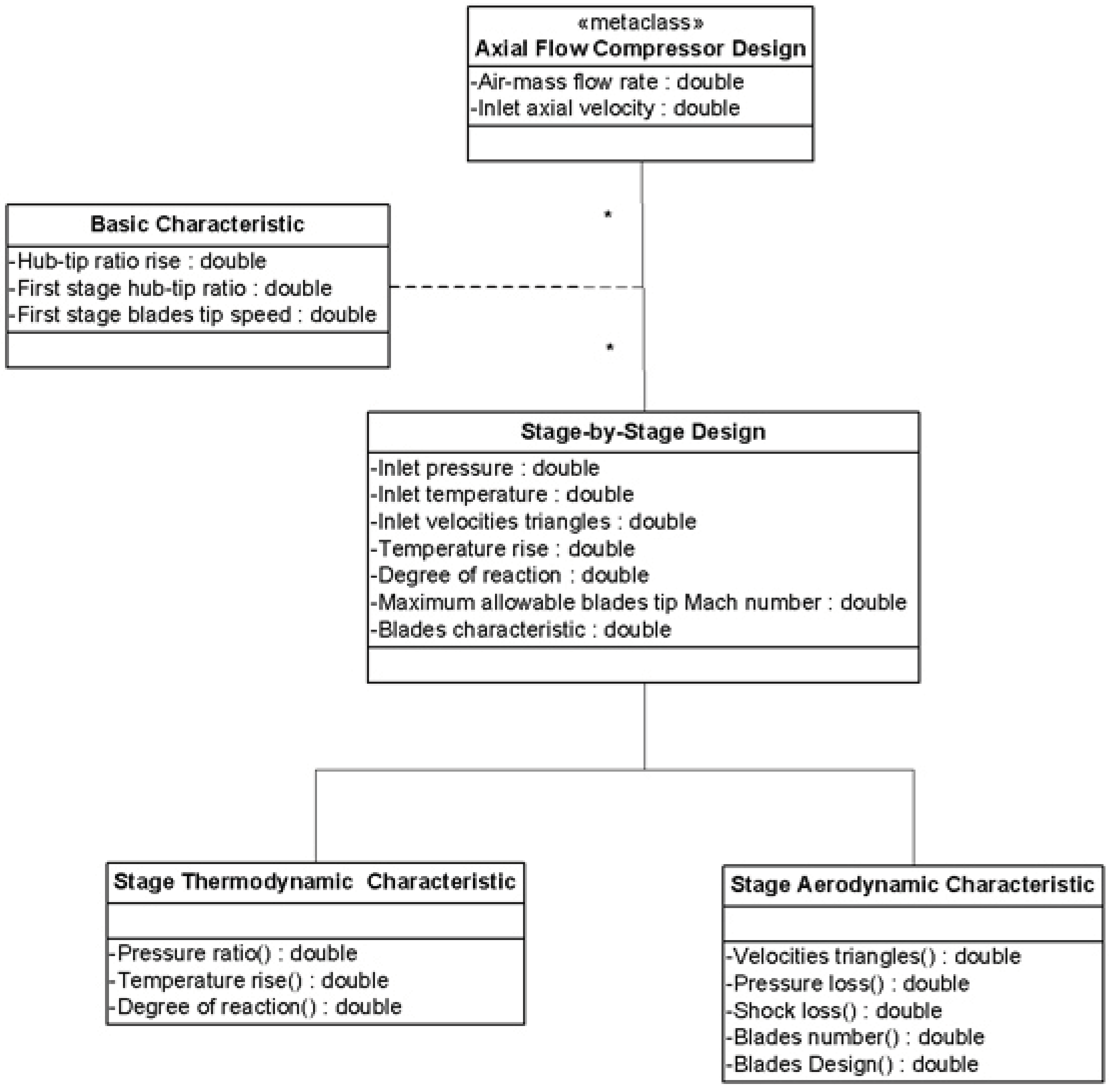

Figure 3: Class diagram for design system of context-aware axial flow compressor.

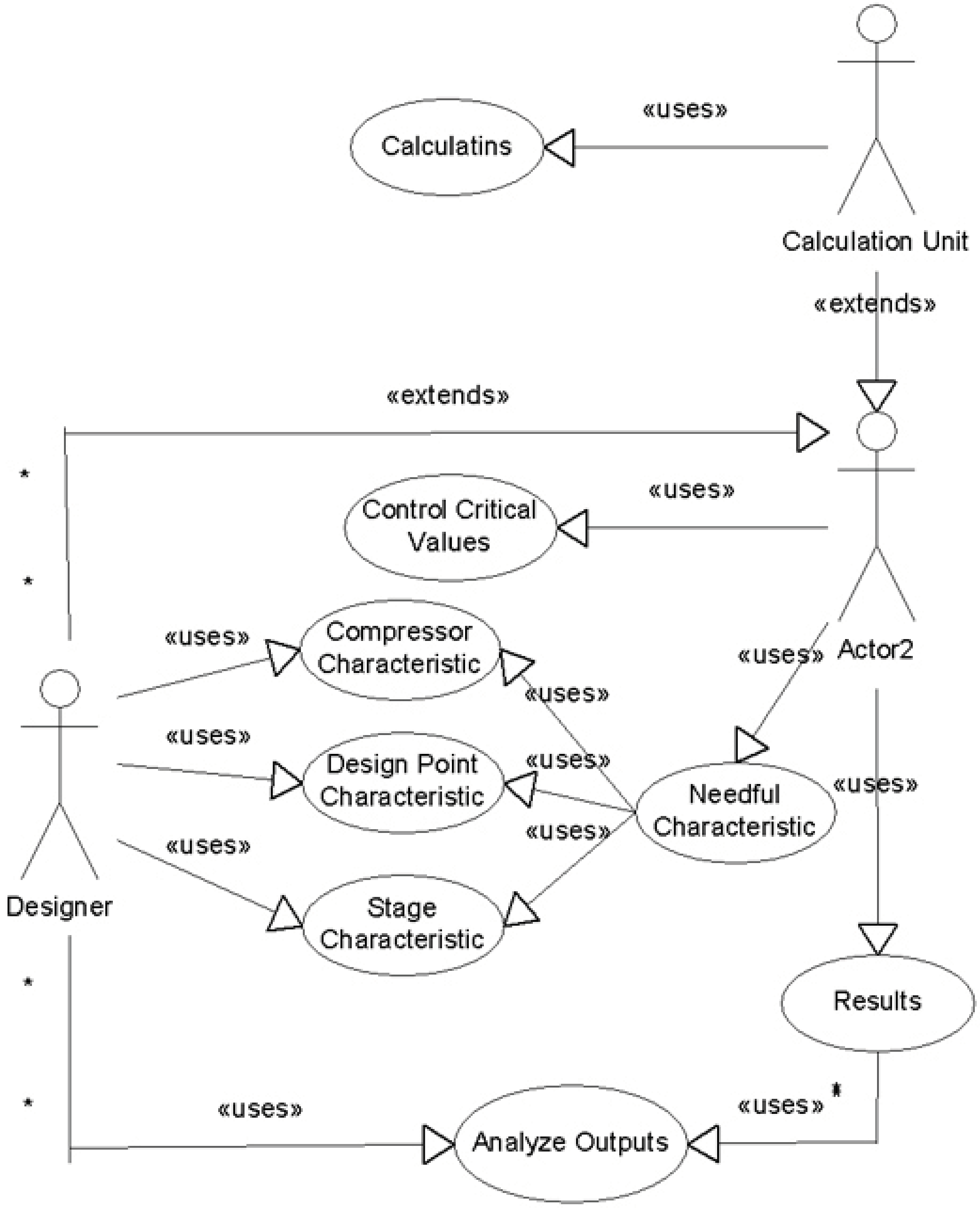

Figure 4: Use-case diagram for design system of context-aware axial flow compressor.

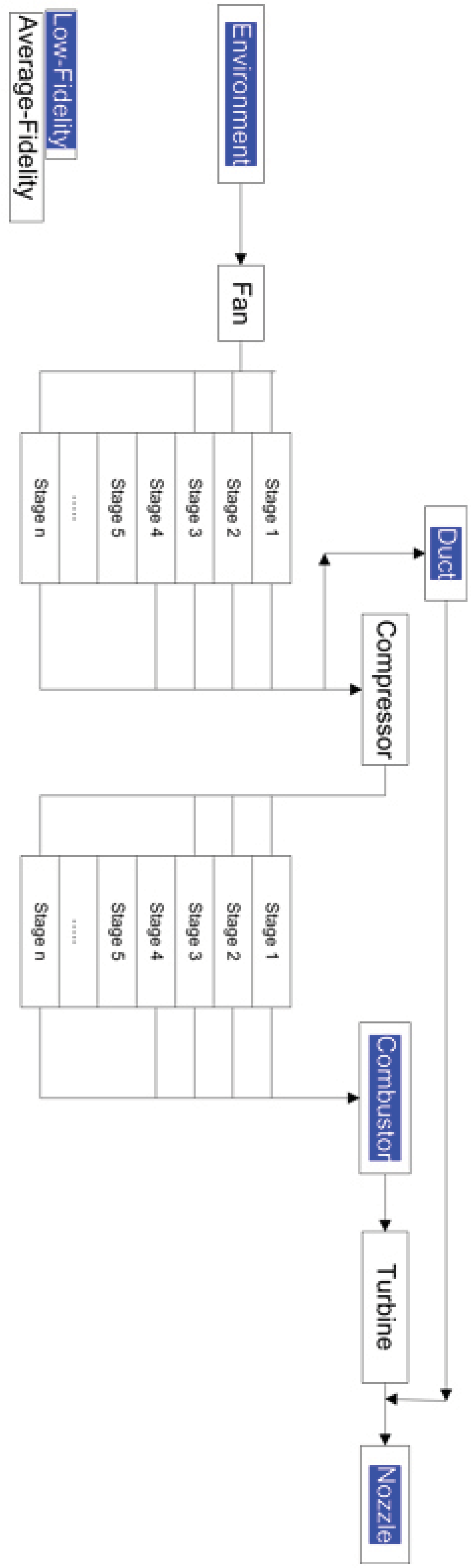

Figure 5: System schematic representing design and analysis level on turbofan engine components

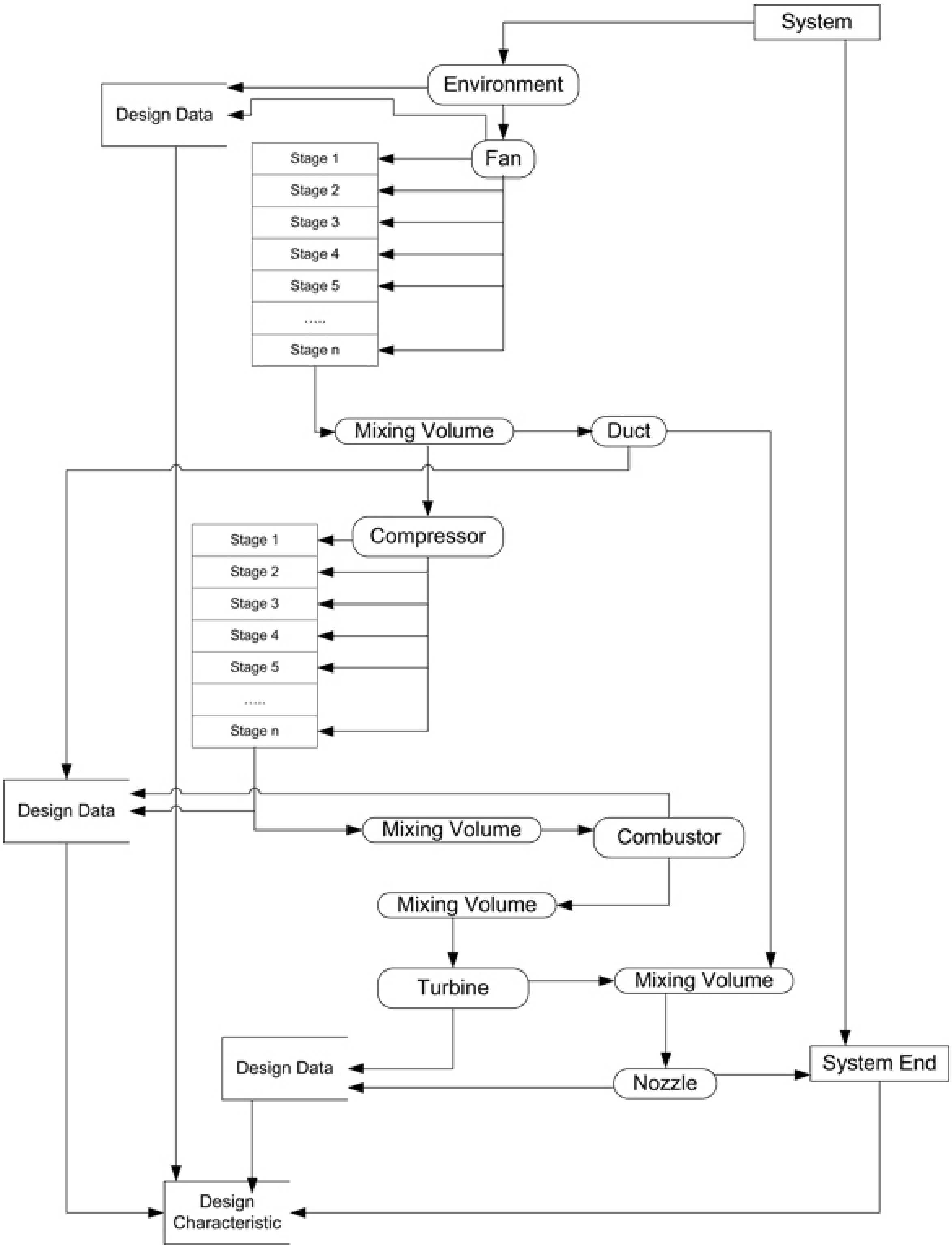

Figure 6: ICCSE turbofan engine model dataflow network

Tables

Class Name	Responsibility	Collaborations
Axial Flow Compressor Design	Inputting inlet axial velocity and air mass flow rate	The base class whose attributes are used in other classes
Rotational Speed & Annulus Dimension	Defining input condition, dimensional characteristic of first stage and compressor rotational speed	Stage Number uses inlet axial velocity and rotational speed to estimate stages temperature rise and number
Stage Number	Estimating temperature rise in each stage and number of stages to deliver given overall pressure ratio	Association class whose operations estimate stages temperature rise needed to design stages
Stage-by-Stage Design	Getting input condition of each stage and starting stage design	Stage Aerodynamic Characteristic and Stage Thermodynamic Characteristic use input condition of each stage to calculate whose characteristic
Stage Thermodynamic Characteristic	Calculating pressure ratio, temperature rise, work done and degree of reaction in each stage	Stage-by-Stage Design uses output pressure and temperature of each stage as input of next stage
Stage Thermodynamic Characteristic	Calculating velocities triangle, pressure and shock losses and blades number and designing blades	Stage-by-Stage Design uses velocities triangles of each stage as input of next stage. Stage Thermodynamic Characteristic uses pressure and shock losses to calculate real stage pressure ratio.
Loss Checking	Checking on pressure and shock losses to assure acceptable values of them	Stage Aerodynamic Characteristic uses results of checking done by this class to set stage aerodynamic characteristic in the acceptable range

Table 1: Table of classes responsibilities-collaborations for design system of conventional axial flow compressors

Class Name	Responsibility	Collaborations
Axial Flow Compressor Design	Inputting inlet axial velocity and air mass flow rate	The base class whose attributes are used in other classes
Basic Characteristic	Inputting basic characteristic of compressor needed to start stage-by-stage design	Stage-by-Stage Design uses this class attributes to define basic structure of compressor
Stage-by-Stage Design	Getting input condition and inputting optional characteristic of each stage and starting stage design	Stage Aerodynamic Characteristic and Stage Thermodynamic Characteristic use input condition and optional characteristic of each stage to calculate whose characteristic
Stage Thermodynamic Characteristic	Calculating pressure ratio, temperature rise, work done and degree of reaction in each stage	Stage-by-Stage Design uses output pressure and temperature of each stage as input of next stage
Stage Thermodynamic Characteristic	Calculating velocities triangle, pressure and shock loss and blades number and designing blades	Stage-by-Stage Design uses velocities triangles of each stage as input of next stage. Stage Thermodynamic Characteristic uses pressure and shock loss to calculate real stage pressure ratio.
Loss Checking	Checking on pressure and shock loss to assure acceptable values of them	Stage Aerodynamic Characteristic uses results of checking done by this class to set stage aerodynamic characteristic in the acceptable range

Table 2: Classes responsibilities-collaborations table of context-aware axial flow compressors design system

Flow status ↓	Regulation status →	Rotational speed is increased	Rotational speed is decreased
Deflection angle at rotor or stator mean radius $\geq 38^{\circ}$		$\otimes$	
Deflection angle at rotor or stator mean radius $\leq 12^{\circ}$			$\otimes$
Shock loss at rotor tip or stator hub < 0 (out of available curve)		$\otimes$	
Shock loss at rotor tip or stator hub ≥ 0.005			$\otimes$

Table.3: Method to regulate rotor rotational speed