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LIFE CYCLE SUPPORT FOR DYNAMIC MODELLING OF GAS TURBINES

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Abstract: In this paper, dynamic modelling of gas turbines is analysed in two aspects, or two dimensions. First, support of the life cycle of the engine and its control system represents a time domain perspective. Second, the concept of unified information space is introduced in order to reflect the interaction of various forms of mathematical models in the "space" dimension. Modern information technologies are then viewed as a means to practically realise the unified information space. *Copyright © 2002 IFAC*

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1. INTRODUCTION

So far, modern information technologies and data processing techniques achieved the level sufficient for creation of an integrated modelling methodology for mathematical modelling and data analysis in regard to gas turbines and their controllers.

Necessary prerequisites might be announced to exist for simultaneous work with static and dynamic engine performance models along with non-linear modelling of large-scale transients and the engine dynamics around steady-state operation. Thus, a unified information space and unified information technology can be developed for creation and use of mathematical models at the life cycle stages of the controller.

Until now, all these tasks required independent techniques for their solving. In particular, the problem of gathering and recording experimental data belonged to specialised institutions and testing facilities. Analysis of static engine performance is performed by mechanical engineers at engine design bureaus. Transient performance of the engine is partially considered by mechanical design engineers and is also investigated by control engineers during control design. Modelling of dynamic properties of the system at steady-state operation is also viewed as an independent task.

Analysis of the variety of mathematical models created at the life cycle stages of the engine and its systems reveals and demonstrates their methodical unity, adequate to the real physical processes and technologies of design and experimental refining of the engine controllers.

However, experimental data, methods and models originated at different stages are employed independently and their interconnection is almost absent. In particular, stochastic modelling techniques are currently weakly connected to the others in the general modelling framework.

The paper is organised as follows. Section 2 considers the variety of mathematical models and their use at the controller life cycle stages. Section 3 provides further insight into the general modelling techniques implemented in industry. The methodical unity of the models is then presented in Section 4 as a prerequisite for organising a unified information space. A concept of a unified information space is introduced in Section 5. Possible software tools are then surveyed in Section 6 to practically implement the proposed unified space for mathematical modelling, identification and control purposes.

2. MODELLING DURING CONTROLLER LIFE CYCLE

Mathematical modelling of gas turbine engines should be viewed in connection with the life cycle stages from design, to demonstration, to commercial control system development, and finally through to in-service use. Through these stages the fidelity of the engine model is refined, as more information becomes available. Thus the models evolve from the initial stages of design, where the general characteristics of the engine are known, to the latter stages, where the controller is tailored to the specific characteristics of the engine.

Mathematical modelling of aero engines is employed at all stages of the life cycle of engine controllers, see Table 1. These are the following:

- design, where general engine performance is analysed and control laws are determined;
- demonstration, tuning and production, where hardware-in-the-loop test facilities employ general models with stochastic elements derived from experimental data;
- in-service use, where condition monitoring, fault diagnosis, adaptation and optimisation of the system are performed using identification methods.

Table 1. Modelling at life cycle stages.

Stage	Model type	Application
Design	Average determined	Control design
Production	Refined determined and stochastic	Quality control
In-service use	Individual determined and stochastic	Condition monitoring, adaptive control

2.1 Life Cycle Stages And Model Implementation.

Different accuracy and degree of detail in modelling are required at various stages. Refining the average models and building individual models requires performing system identification, mostly in closed-loop control. The models obtained are then used for adaptive/optimal control and condition monitoring purposes (Gertler, 1998).

Complication of engine control systems and increase of aircraft requirements have resulted in the necessity to use on-board computers in automatic control systems in addition to, or instead of hydraulic and pneumatic parts of computing aero control systems. Note that most actuators are still hydraulic and pneumatic devices.

Computational capabilities of modern on-board computers enable optimisation of control programs to be performed accounting for flight conditions and individual characteristics of the engine. Simultaneously with current control, optimal automatic adjustment of control programs can also be realised. This requires new control methods to be developed.

The factors mentioned above require current correction of the "nominal" conventional control program for actual engine characteristics and flight conditions. Computer-based electronic control systems open possibilities for adaptive correction of control programs with feedback on global optimisation criteria.

Conventional approaches to engine control design consist of optimisation of control programs for a generalised engine and average flight conditions. Therefore, the best values of controlled parameters deviate from that expected because of characteristic deviation of engine units, gradual wearing of the engine and changes in the engine operation conditions.

Modern aero engines possess a large number of control factors. This creates necessary conditions for optimising the operation of the power plant and aircraft as a whole using an on-board computer controller.

The potential to incorporate optimising control in modern digital controllers offers great opportunities for minimisation of fuel consumption leading to greater range and reduced emissions. In addition, the control system can be optimised to reduce stress on engine components leading to reduced maintenance costs and greater longevity.

Experimentation with open-loop control often is not allowed from the safety viewpoint. Moreover, adaptive control systems require closed-loop identification, by definition. Such identification tests allow the plant model to be obtained under some conditions referred to as identifiability conditions (Arkov, *et al.*, 2000).

In practice, the engine and its controller are designed simultaneously and co-operatively tested. Therefore, the engine and controller are an inseparable integrated unit, consisting of transducers, converters, digital control electronics and actuators. The system has to be modelled as a whole considering the transducers and actuators to be part of the plant. Within this framework the control algorithms can be adjusted to provide the desired levels of performance. The key modelling techniques required over the life cycle stages are given below.

2.2 *Non-Linear Performance-Based Modelling.*

The detailed non-linear static model is represented by the following system:

$$\begin{cases} \mathbf{f}_x(\mathbf{X},\mathbf{U},\mathbf{V}) = \mathbf{0} \\ \mathbf{Y} = \mathbf{f}_y(\mathbf{X},\mathbf{U},\mathbf{V}) \end{cases}; \tag{1}$$

where **X** is the state vector, **U** is the control vector, **V** is the flight atmospheric conditions vector, and **Y** is the observed coordinates vector.

2.3 *Dynamic Characteristic Modelling.*

The dynamic characteristic is a graphical image of the non-linear dynamic model. In addition to the static line $\dot{n}$=0, the characteristic of a single-shaft engine also includes a set of lines of constant accelerations $\dot{n}$=*const*. Its derivation from the detailed dynamic model is performed by means of setting up the control laws upon shaft speeds n, compressor pressures p_c and turbine temperatures T_t and calculating the corresponding lines in the engine parameters plane with the axes: "shaft speed *versus* fuel flow":

$$\dot{n}=const,\ p_c=const,\ T_t=\mathrm{const}\ . \tag{2}$$

2.4 *Linear Dynamic Modelling.*

Linear dynamic models (LDM) are obtained from performance-based models via linearisation or identification methods. Also, they can be estimated from experimental data. Linear dynamic models are usually utilised in the form of state-space equations, transfer functions or Bode diagrams (Isermann, 1981). These describe engine dynamics around a steady-state operating point. However, when exploring control programs for transient operation, linear models should incorporate non-linear properties of the engine.

2.5 *Real-Time Dynamic Modelling.*

The real-time piecewise linear dynamic model (RPLDM) combines the engine non-linearity and the LDM linearity. The source data for building the RPLDM are the non-linear static lines and the LDM coefficients (Kulikov, *et al.*, 1999). The static line parameters between these points are then determined by means of interpolation. For the LDM coefficients, interpolation is used in the same manner. The calculation relationships establish the link between **A**, **B**, **C**, and **D** matrices of the LDM coefficients and the static line coordinates $\mathbf{X}_{st}$, $\mathbf{U}_{st}$, and $\mathbf{Y}_{st}$ by means of the operating parameter η :

$$\begin{aligned} \dot{\mathbf{X}}(t) &= \mathbf{A}(\eta)\big(\mathbf{X}(t)-\mathbf{X}_{st}(t)\big)+\mathbf{B}(\eta)\big(\mathbf{U}(t)-\mathbf{U}_{st}(t)\big), \\ \mathbf{Y}(t) &= \mathbf{C}(\eta)\big(\mathbf{X}(t)-\mathbf{X}_{st}(t)\big)+\mathbf{D}(\eta)\big(\mathbf{U}(t)-\mathbf{U}_{st}(t)\big)+\mathbf{Y}_{st}, \\ \eta &= \sum_{i=1}^{n} z_i x_i(t)\ . \end{aligned} \tag{3}$$

2.6 *Markov Modelling.*

A stochastic model in the form a Markov chain is described with the stochastic matrix of transition probabilities P. Each element of the matrix represents the probability of the transition from the state X_j to the state X_k over the sampling period $T_s = t_n - t_{n-1}$:

$$P_{ij} = Prob\{X(t_n)=X_j \mid X(t_{n-1})=X_i\};\quad \sum_{i=1}^{m} P_{ij} = 1\ . \tag{4}$$

Accounting for the stochastic part of the engine dynamics enables the control laws to be adjusted to noise performance and to the individual engine characteristics.

3. APPROACHES TO MODELLING OF GAS TURBINES

Two major trends (or approaches) can be defined in mathematical modelling of gas turbines and their systems at the life cycle stages.

The first approach uses the models as a means for solving scientific and engineering problems. Technical problems are considered a set of successive and interconnected tasks. To solve every task, a separate modelling tool is to be applied, often being independent of other tools.

Another trend integrates the tasks using detailed non-linear thermodynamic models, being promoted by central R&D institutions, e.g. Central Institute for Aero Engines. In the second case, all the tasks are oriented towards the building, using and refining of non-linear models, including systems identification and control optimisation. In a simplified form, non-linear regression models are proposed for control engineering purposes.

The practice of design of engine control systems at most institutions and bureaus often combines both approaches. This combination will be investigated below in the view of possible ways for automation and creation of unified information and modelling space.

So far, a unified tool for modelling of gas turbines has not been created, compare Unified Modelling Language (UML) for information systems modelling (Fowler and Scott, 1997). Hence, codification of modelling experience accumulated and positioning of unified information space for the life cycle stages represents a topical problem in mechanical and control engineering. The problem becomes even more urgent for the stages where experimental data are available and identification becomes possible.

Currently, identification is conducted at various life cycle stages independently (Arkov, *et al.*, 2000). Interaction of the models created and modelling techniques employed is of a great difficulty.

4. HOMOMORPHISM OF ENGINE MODELS

In this section, some common structural properties of mathematical models are surveyed. Analysis will demonstrate how these preserve during models' transforms at the life cycle stages.

In design of aero engines and their systems, determined mathematical models are mostly used. The design techniques employed are also oriented at determined models. However, the use of stochastic models enables the problems of stability, accuracy, interference protection and reliability to be more thoroughly investigated. In order to create such models, a volume of statistics should be gathered and processed in regard to a long period and over the fleet, i.e. in time and space. This requirement is the corollary of the prerequisites for the use of statistical methods operating on stationary and ergodic processes only.

Note that different kinds of models reflect the same structural properties of the engine in the aspect of automatic control. This unity has a connection with the concept of homomorphism as given by Mesarovich and Takahara (1975), referring to the general systems theory. It is viewed in connection with a set of chosen system's properties. It can also be considered a two-way mapping of two sets preserving their essential structural properties.

Control engineering practice in aerospace has proven non-linear thermodynamic models to be accurate and adequate enough for design and analysis of the engine controller. During the controller's life cycle, various transforms are conducted over the models including linearisation and time quantisation. Most models are simplified compared to the performance-based thermodynamic models. Moreover, these represent the engine's behaviour in a small neighbourhood of an operating point, see Figure 1.

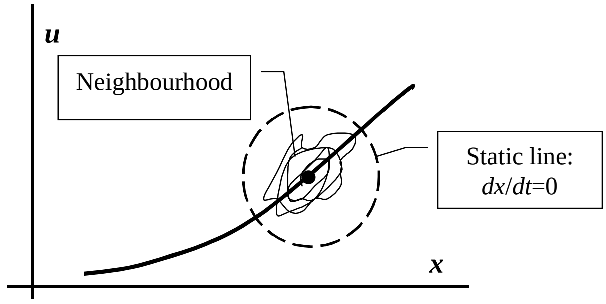

Fig.1. Dynamic process around static point.

A representative of the class of stochastic models is the Markov chain recently introduced in dynamic modelling of gas turbines by Arkov, *et al.* (1997). The appropriation of their use in this area is based on homomorphism of the models and their transforms.

It can be demonstrated that at each transform the models' homomorphism preserves. Furthermore, a composition of homomorphisms is also a homomorphism. This embraces such essential properties as listed below:

- the order of a differential or difference equation;
- system's stability;
- general shape of the transients under standard inputs;
- matching of the transients with some accuracy;
- Markov properties of the system.

Therefore, using $\boldsymbol{C}$ to denote the listed system's properties, a concept of ***C**-homomorphism* is then investigated.

In practice, one should consider $\boldsymbol{C}$-homomorphism of models with some degree of accuracy $\boldsymbol{\varepsilon}$. Furthermore, a small neighbourhood of a fixed operating point is analysed, so *local **C**-homomorphism* is to be considered, expressing the methodical unity of the models.

5. UNIFIED INFORMATION AND MODELLING SPACE

The previous sections gave a general overview of the variety of mathematical models derived at the controller life cycle stages. In addition, during simulation and experimentation, a huge amount of data records appear in different forms and formats. In order to effectively handle the increasing volume of data, a new concept of a unified information space is introduced below.

Three major dimensions of the unified information space are presented in Figure 2 as follows:

- types of mathematical models;
- the controller's life cycle stages;
- the company or division dealing with the models.

A model or data placed in the information space should interact with other models/data available to the user. This involves a sort of interaction between companies and their divisions on the subject of modelling and experimental data. Due to long distances between companies involved in aero engine design and production and their hierarchical administration structure, paper documents cannot provide the means for effective interaction between engineers. In this case, only information technologies based on distributed computing might assist in arranging the unified information space.

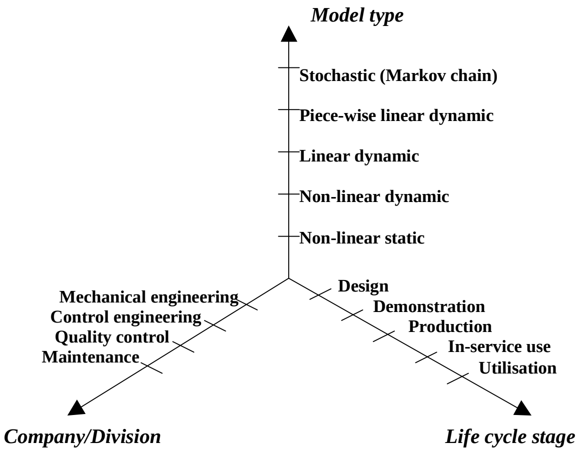

Fig.2. Major dimensions of information space.

When considering unification of the information space, one should provide standardised interaction and compatibility of the various models and data used. In terms of data base theory, all the models must be *actualised*, i.e. made instantly available for the users. Moreover, any change in one particular model (e.g. LDM refined using identification) is to be reproduced or replicated in all other forms of the models. At least, a reference to the changed model should be available to the customers.

Life cycle support based on information technologies was introduced as the Continuous Acquisition and Life Cycle Support (CALS) strategy, see for example Molina, *et al*. (1999). However, CALS standards developed so far mostly concern mechanical engineering data exchange and universal low-level formats for data files, which is not sufficient for shared control engineering data.

Life cycle support of control systems and their mathematical models is still to be developed along with creating specifications for logical data structures to organise models' interaction, which is presented here.

The advent of standard methodologies for structural modelling and design of information systems like Structured Analysis and Design Technique (SADT) with the supporting software Design/IDEF (Integrated DEFinition) made it possible to formalise and codify the existing, evolutionary formed modelling techniques for gas turbines and their systems (Marca and McGowan, 1988).

In the modern practice of information systems design, the formal description of information processes usually precedes automation of existing manual and paper-based business processes. Re-engineering represents computer-aided improvement of existing organisational management to increase the effectiveness of the enterprise as a whole.

The concept of unified information space embracing life cycle support enables an iterative improvement technique to be employed in the framework of an information system for controller design and refinement, see Figure 3. Its application will certainly save much efforts and investments dedicated to improving control performance.

6. INFORMATION SPACE: PRACTICAL ASPECTS

During the creation of the unified information space a formal description of the modelling techniques and information processes is conducted. This requires the use of computer-aided tools for system modelling. In particular, SADT/IDEF methodology is very promising for analysis and organisation of the information space.

These system modelling tools were originally developed within defence ministries and departments, then were broadly used by civil industry in the West, and recently were recommended as a standard for information systems design in Russian industry. Furthermore, in developing the information system structure, the general trend of data and information integration is accounted for in regard to the information originating at various life cycle stages, as defined by CALS standards.

A formal IDEF definition is then used for systematic description of the models and methods connected with them. An aligned integration of experimental data obtained from various sources and at different stages is also performed using IDEF standard diagrams, see Figure 3. Note that IDEF diagrams present events and functions operating simultaneously, unlike the block diagram for algorithms which shows sequential events.

Modern information technologies enable to form a unified information space for the integrated use of mathematical modelling methods by both mechanical and control engineers. An initial approach to the problem has been made at a scientific production enterprise during the design of a controller for a promising turbo prop fan. Based on the approach proposed, a standardisation framework is to be developed in the nearest future.

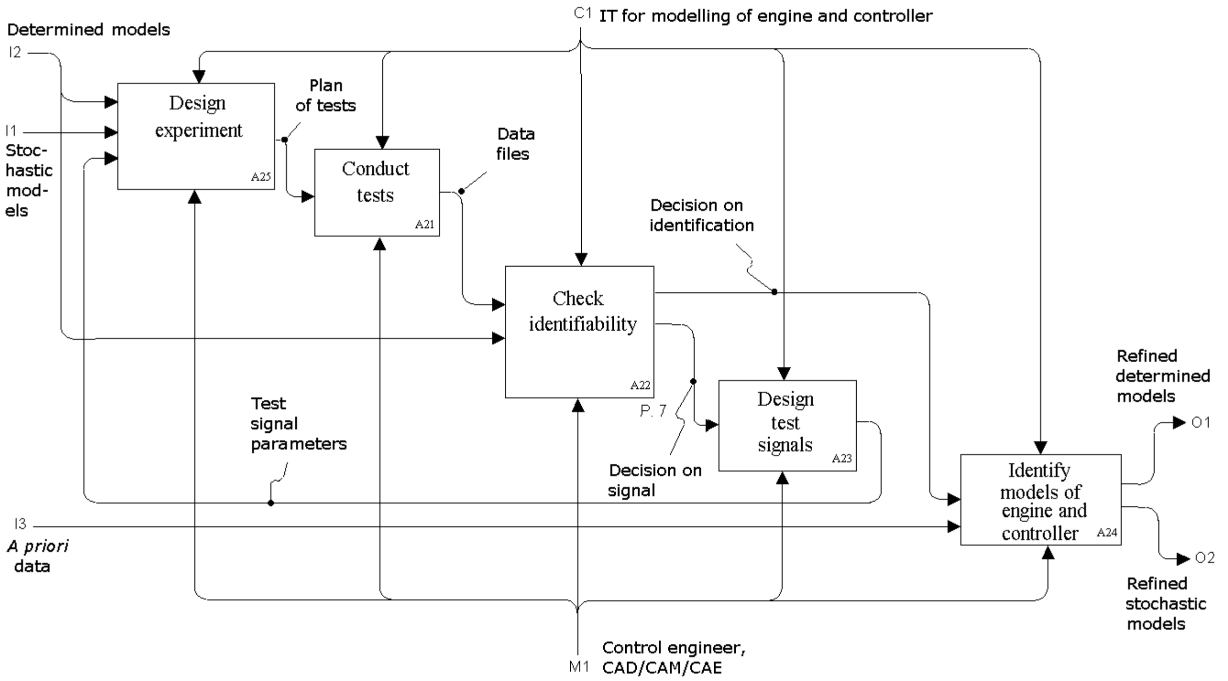

Fig.3. Identification iterative loop within information system.

An information technology was designed for experimental data gathering and recording followed by analysis of static and dynamic performance of the engine and its controller. A data logging system is connected to the MATLAB (MATrix LABoratory by MathWorks) interactive computing environment along with VisSim and the SIMULINK visual modelling tools (Kulikov, *et al.*, 1999). In the design diagram, the outer loop embraces the stages of modelling, simulation, experiments, identification, and model refinement.

One of subsystems here is data gathering, identifiability monitoring, estimation of models and introduction of artificial perturbations, if necessary. After new tests, identification is carried out again and the whole cycle is repeated until identifiability is ensured. Thus, some iterative loops are introduced for gradual model refinement. Data and model integration in the unified space enables to improve the overall performance of the design process and increase the accuracy of the models obtained. Eventually, a model repository is created connected with the modelling techniques and a collection/warehouse of data records.

4. CONCLUSION

The paper presented a new concept of a unified information space for mathematical modelling of gas turbines and their controllers. The proposed information space unifies various models and data originated at the controller's life cycle stages. Standard system modelling methodologies and software tools were chosen to rapidly implement the new concept in Russian aerospace industry. Application of the unified information space will enable control quality to be improved along with greatly reduced investments.

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