QUALITATIVE MODELING IN THE TURBOJET ENGINE DOMAIN

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ABSTRACT

This paper addresses some of the issues involved in modeling the domain of turbojet engine operation. A causal model based on the relationships between engine parameters has been developed and used to implement an engine simulation. The implementation includes a facility for explaining the results of the simulation.

I INTRODUCTION AND MOTIVATION

Several theories of mechanism modeling such as Common Sense Reasoning [2], Incremental Qualitative Analysis (IQ) [3], and Qualitative Process (QP) Theory [4] have been proposed in recent years. The application of these theories has been limited to a narrow set of domains, such as the electronic circuit analysis domain, the operation of a steam plant, and domains with simple processes involving motion. Electronic circuit analysis has been by far the most popular domain, with applications including simulation, circuit recognition, and troubleshooting.

Like the electronics domain, the turbojet engine has been studied extensively, and presents a rich domain for mechanism modeling. However, unlike the electronics domain, where the number of individual parameters is small (current, voltages, etc.), and where the number and function of components can vary (a transistor can function in one of several different ways), the aircraft engine is a fixed device, and is described by hundreds of parameters. Furthermore, both the relationships between engine parameters and the operational limits of the engine are often described by complex non-monotonic functions.

Proper qualitative models of the engine will be useful for several reasons. (1) Numerical simulators, while providing a large amount of quantitative information, have only limited capabilities for explaining the results that are obtained. A qualitative model can be used to explain the results in an efficient manner. (2) As in other domains, qualitative reasoning may be useful for constraining the number of equations which need to be solved by a quantitative model. (3) Prediction and troubleshooting may be possible, and will be useful in aiding mechanics and pilots. Qualitative models would be especially useful if warnings of potential failures could be given to the pilot, along with suggestions for avoiding these failures. (4) Finally, a qualitative model will be faster and less expensive to use than a quantitative model. Can a qualitative model be designed which is capable of achieving the above goals? What information should be included in such a model? What are the limitations of such a model? These are the kinds of questions we have addressed in our research, which is an attempt to demonstrate the feasibility of such a qualitative simulator.

II TEXTBOOK DESCRIPTIONS OF THE ENGINE

The feasibility of a qualitative engine model is strongly supported by the fact that a substantial portion of basic textbook descriptions of engine operation is qualitative in nature [5,6].

Basic textbook descriptions of the engine concentrate on operational parameters (e.g., temperatures, pressures, air flows, fuel flows, etc.). These descriptions include (1) specifications of causal connections between parameters (e.g., "As the ambient (environment) temperature increases, compression ratio tends to decrease)."، (2) descriptions of limits (e.g.,"If the angle of attack is too high, stall will result."), and (3) effects of variable structures such as bleed air ports (similar to a valve). In addition, descriptions of the underlying processes in the engine provide the framework to which all other descriptions are tied.

In order to fully "understand" the operation of the engine, it is important to include as much of the available information as possible. The current model may be looked upon as a causal model (our focus is on the relationships which exist between engine parameters), and includes information belonging to categories (1) and (2) above.

III THE CAUSAL MODEL

A causal model of turbojet engine operation requires that the relationships which exist between engine parameters be represented. It has been observed that in basic engine texts, complex multi-parameter relationships are broken down and described through the relationships which exist

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**A detailed description of the ideas presented in this paper may be found in [1]. This work has been supported by the Air Force Office of Scientific Research under contract number F49620-82-K-0009.

between pairs of component parameters. This greatly simplifies the complexity of parameter relationships; while multi-parameter relationships are often non-monotonic in nature, a large percentage of the relationships which exist between component parameter pairs are described by monotonic functions.

Monotonic relationships between parameters can be reasoned about in the following manner, as has been described in [3,4]:

A <u>monotonically proportional relationship</u> (<u>MPR</u>) between two parameters, A and B, implies that a qualitative change in one parameter induces a like change in the other (e.g., if A increases, then B also increases). In the current model, an MPR is denoted by the symbol "I+".

A <u>monotonically inverse proportional relationship</u> (<u>MIPR</u>) between two parameters implies that a qualitative change in one parameter induces an opposite change in the other (e.g., if A increases, then B decreases) and is represented by the symbol "I-".

A. <u>Non-monotonic Relationships</u>

In addition to the simple monotonic relationships described above, relationships between parameters can also be described by non-monotonic curves. Such cases are denoted by the symbol "I". As in previous work, non-monotonic curves are reasoned about by breaking such curves into monotonic components at inflection points. However, unlike past work, where each non-monotonic relationship in the domain has been represented individually, a more general approach of representing non-monotonic relationships is employed in our model. Generic models of possible non-monotonic curves, such as concave-down and certain piecewise linear curves, have been developed and applied to individual cases.

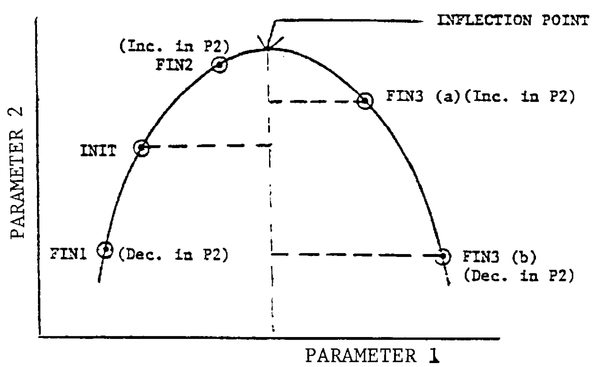


Figure 1. A Generic Concave-Down Curve

As an example, consider the relationship between fuel-air ratio and combustion efficiency, which is described by a concave-down curve, and which has an inflection point at a value of fuel air ratio of .0625. In the current model, this relationship is represented by:

```
( (combustor fuel-air-ratio)
  (combustor efficiency)
  concave-down .0625        )
```

In order to reason about efficiency effects, this particular instance is applied to a model of a generic concave-down curve.

Consider the generic concave-down curve given in Figure 1. Let us suppose that we know the initial values of the variables. This curve may be broken at the inflection point and reasoned about as follows:

Let the parameter on the X axis be known as "A" (fuel-air ratio) and the one on the Y axis be known as "B" (efficiency). The inflection point of the curve is known (.0625), as well as the initial value of A and its derivative change (i.e., increase or decrease).

(1) If the initial value of A is less than the inflection point (.0625), and if A decreases, then B decreases. The same holds if the initial value of A is greater than the inflection point, and A increases.

(2) Otherwise, multiple paths are possible, and the final value of A is required for further reasoning. If both the initial and final values of A lie on the same side of the inflection point, i.e., both values are less than or greater than the inflection point, then B increases.

(3) In the final case, the absolute values of the difference between (i) the inflection point and the initial value and (ii) the difference in the inflection point and the final value are compared. If the initial value difference (i) is smaller, then B decreases. If the final value difference (ii) is smaller, then B increases.

B. <u>Time</u>

The current model also includes a crude representation of the time taken for the change in one parameter to propagate to the other. This time is not an exact "real" time, but a comparison with other relationships. For example, the relationship between altitude and air density is a concurrent change, while a finite delay is encountered as the effects of a change in density propagate and cause a change in compressor parameters.

Even this crude representation of time has its utility. One of the possible uses of a qualitative model is in aiding the pilot. Assume that the turbine inlet temperature was approaching its limit. Although both a change in the throttle setting and in the airflow into the engine could eventually lower turbine temperature, the primary suggestion will be to change the throttle setting, because of the relatively shorter delay between its change and its effect.

Relationships in the model are represented as follows:

```
( parameter1 type-of-relationship parameter2
  time-delay)
```

An example of the same is:

((environment altitude) I- (environment density) 0)

The rule above indicates that altitude and density share an I- relationship, and that there is no delay between changes in altitude and density.

Note that the same rule can be used for both simulation and diagnosis. Given a change in altitude, the change in density is found by indexing along the left-hand side of the rule. The causes of a change in density can be found by indexing along the right-hand side.

IV OPERATIONAL LIMITS

A representation of the operational limits of a domain is mandatory for a useful qualitative model. The operational limits of the engine may be dependent upon the value of a single parameter (e.g., turbine inlet temperature should not exceed 1650 degrees R.) or be described by a multi-parameter curves of varying complexity (monotonic curves, parabolas, or even closed geometric figures such as ellipses). The current model includes only single parameter limits; however, a technique for reasoning about multi-parameter operational limits is discussed later in this section.

Single parameter limits are represented by IF-THEN rules with built-in quantifying conditions. The quantifying conditions employ the results of a simulation to determine if any limit at all could have been exceeded. The limit rule for the turbine inlet-temperature limit is given below:

```
(If (is-increasing '(turbine inlet-temperature))
  then
    (if (greaterp (get-newval '(turbine
    inlet-temperature)) 1650)
      then (printout T "approaching turbine
      inlet-temperature limit")]
```

This statement indicates that, if turbine inlet temperature is increasing, exceeding the limit is possible, and a check to determine if the value has exceeded 1650 degrees R. is carried out.

Multi-parameter limits are not easily modeled by IF-THEN rules since such limits are described by complex curves rather than a single value. One method of handling such curves is to model the curves themselves.

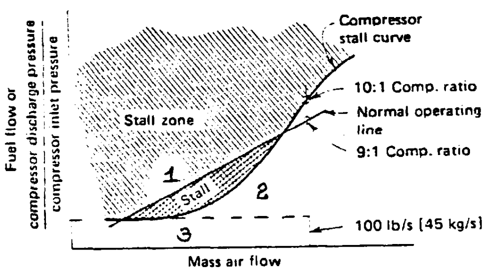


Figure 2. Compressor Stall Curve

Consider the compressor stall curve (Figure 2) where, if the state of the engine falls in region 1, stall is likely. To model such a curve, the individual regions have to be defined, and connections between them specified (e.g., region 1 is the stall region and is connected to all other regions). In addition, heuristics have to be specified which connect parameter changes to regions which may be entered. For the stall curve, such heuristics will include "both regions 1 and 2 may be entered from region 3 if compression ratio increases" and "(in the event of a decrease in massflow) the only new region which may be entered from region 2 is region 1."

Now assume that the initial operating point is known. From this initial point, the regions which may be entered can be determined using the results of a qualitative simulation, which provides all necessary information regarding the qualitative change in any parameter. Quantitative knowledge will be necessary to determine in which of the possible regions the final steady state condition will reside.

V SIMULATION

The qualitative simulation essentially consists of a propagation of constraints. For the current model, the constraints are increases and decreases in parameters. As determined in the earlier work [3], any case where a parameter does not change is unimportant. Figure 3 demonstrates the results of increases in airspeed (EA) and throttle setting (CKTS) for our simulation. In the figure, changes in parameters are given by + (increase) and - (decrease). Non-monotonic relationships which depend upon the state of the engine are represented by the symbol "I".

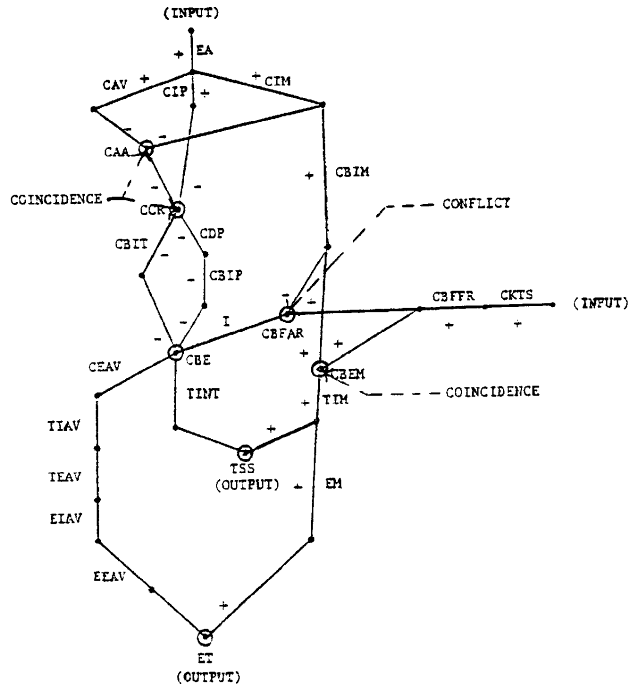
The figure is labelled using the following scheme: Normally, a link is labelled with a parameter and the qualitative change in that parameter. The case of an "interesting point" is represented by a circled node, the node itself is associated with a parameter, with links leading to that node being marked with the "influence" of preceding changes on the node.

Any point where branches merge have been marked as "interesting points". At these points a coincidence (the merging of like changes) or a conflict (the merging of opposite changes) occurs. In the figure, a coincidence occurs when changes in the compressor inlet-pressure (CIP) and compressor angle-of-attack (CAA) both cause a decrease in the compression-ratio (CCR). A conflict occurs when the combustor inlet-massflow (CBIM) and the fuel-flow-rate (CBFFR) have opposing effects on the fuel-air-ratio (CBFAR).

Note that the "I" relationship between fuel-air-ratio and the efficiency (CBE) cannot be resolved until the conflict regarding fuel-air-ratio is likewise resolved. Conflicts are the bottlenecks of such a qualitative simulation.

A. Resolution of Conflicts

In the past, conflicts have been resolved in two ways:



LEGEND

EA - (Environment Airspeed)
CAV - (Compressor Airflow-Velocity)
CIP - (Compressor Inlet-Pressure)
CIM - (Compressor Inlet-Massflow)
CAA - (Compressor Angle-Of-Attack)
CCR - (Compressor Compression-Ratio)
CDP - (Compressor Discharge-Pressure)
CBEM - (Combustor Exit-Massflow)
CBFAR - (Combustor Fuel-Air-Ratio)
CBIM - (Combustor Inlet-Massflow)
CBIT - (Combustor Inlet-Temperature)
CBIP - (Combustor Inlet-Pressure)
CBFFR - (Combustor Fuel-Flow-Rate)
CBE - (Combustor Efficiency)

CBEAV - (Combustor Exit-Airflow-Velocity)
TIAV - (Turbine Inlet-Airflow-Velocity)
TINT - (Turbine Inlet-Temperature)
TEAV - (Turbine Exit-Airflow-Velocity)
EIAV - (Exhaust Inlet-Airflow-Velocity)
EEAV - (Exhaust Exit-Airflow-Velocity)
TIM - (Turbine Inlet-Massflow)
TSS - (Turbine Shaft-Speed)
EM - (Exhaust Massflow)
ET - (Exhaust Thrust)
CKTS - (Cockpit Throttle-Setting)

\+ --> INCREASE
\- --> DECREASE
I --> NON-MONOTONIC FUNCTIONAL RELATIONSHIP
NO SIGN --> DEPENDS UPON PREVIOUS RESULT
--> INTERESTING POINTS

Figure 3. Effects of an Increases in Airspeed and Throttle Setting

(1) In cases where both initial and final (desired state) values were either available or calculable, a simple subtraction resolved the conflict. This technique can be employed when diagnosis (analysis) is the intended application, since both initial and final values are known. In addition, numerical values may also be obtained when a qualitative simulation is used to constrain a quantitative one. An example of this possibility is provided by de Kleer in his model of the roller coaster domain [7].

(2) The most popular technique of conflict resolution has been the simulation of all possible paths of change by propagation of both an increase and a decrease after a conflict. External information is then used to select one among the different possibilities.

This technique is also applicable to the engine domain. If both an increase and a decrease were propagated at the conflict in fuel-air-ratio (CBFAR) in Figure 3, individual paths will exist which lead to either an increase or a decrease in thrust (ET).

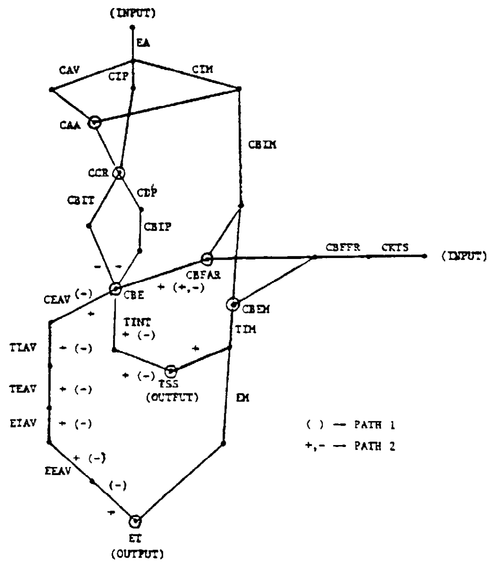


Figure 4. Possible Paths Leading to a Change in Thrust

Figure 4 shows these possible paths (all unmarked links in Figure 4 are described by an I+ relationship). If it were desired that thrust should decrease, then path 1 can be chosen as the only applicable path. Since in path 1 efficiency (CBE) decreases, the effect of fuel-air ratio (CBFAR) on efficiency can be either an increase or decrease.

VI POSSIBLE APPLICATIONS OF A QUALITATIVE ENGINE MODEL

Other than simulation, there are several possible applications of proper qualitative engine models. These include (1) the explanation and analysis of the results of a simulation, (2) constraining the equations which need be solved by a numerical simulator, and (3) as a pilot's aide.

A prototype facility for the explanation of a numerical simulator's results has been implemented. The cause of any change in an engine parameter can be provided. When requested, coincidences and conflicts can also be noted and explained. Further capabilities can be added as the model expands to include more information and relationships of the engine.

As in the roller coaster domain [7], a qualitative-quantitative engine simulator can conceivably work in the following manner: wherever possible, linearized equations can be solved except for certains regions of interest. These regions of interest can be determined by the qualitative portion of the simulation, i.e., through the detection of unresolvable conflicts and non-monotonic relationships. A limitation of this technique is that many of the equations which describe the engine cannot be linearized.

The fact that a qualitative simulation is capable of identifying many possible paths will be useful in warning of different parameter limits that are likely to be exceeded and for providing suggestions for avoiding the same. If the engine is operating near a limit, the identification of connections to the input parameters, or of conflicts along a path leading to the limit will provide insight in determining which input parameter should be changed. Complications are possible since for a given input change, multiple paths of change are possible.

Consider path 1 as shown in Figure 4. Under the right circumstances, it is possible that an increase in throttle-setting causes either an increase or a decrease in thrust (e.g., a decrease is caused by path 1, and an increase is caused by the right-hand link, as shown in Figure 3). If an increase in thrust were desired, it is not clear what the change in throttle setting should be since such a change can lead to either an increase or a decrease in thrust.

VII LIMITATIONS

One of the major limitations of qualitative models of the engine is that transient analysis is not possible. Thus, the effects of the feedback path between the turbine and the compressor cannot be fully appreciated. Due to the effects of feedback, certain operational parameters often increase and decrease a number of times before reaching a steady state condition. With current mechanism modeling techniques, it is only possible to determine whether a system is exhibiting positive or negative feedback. While this recognition capability is not sufficient during a simulation, such a capability can enhance the capabilities of an explanation facility.

In order to really "understand" a device, it is important to know its purpose. In the engine domain, an understanding of the purpose is only partially achieved by a representation of the underlying processes which cause parameter changes.

In representing processes, the notion of a structural hierarchy is lost. The process of compression in the compressor is a result of several individual processes: the flow of air through the compressor, the rotation of the compressor, and the action of the compressor blades and vanes on the air passing through them. While all these processes are important, it is not an easy task to represent the complex aerodynamic relationships of the air flow passing through the engine.

Finally, a complete model of the engine will need to include the effects of parts whose state can vary. These include such parts as variable inlet guide vanes, variable exhaust nozzles, and bleed airports.

ACKNOWLEDGMENTS

The author would like to thank the people who have helped the progress of this research in many countless ways: Prof. David Waltz, my thesis advisor, Prof. Gerald DeJong, Cathy Cassells, Shahid Siddiqi, and all the members of the CSL AI Group at the University of Illinois.

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