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DEVELOPMENT OF AN ENERGY MANAGEMENT PFD USING TOTAL ENERGY CONTROL PRINCIPLES

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ABSTRACT

Navigation accidents can be classified into a number of root causes. Lack of energy awareness is identified as a systematic cause of aviation incidents and accidents. A new format of the Primary Flight Display has been developed to increase the pilots awareness of the aircraft's energy state. In this display format, energy relations between speed and altitude are directly visualized, together with the relations between their derivatives: acceleration and vertical speed. It is hypothesized that the method of visualization described in this paper also allows decoupling of the control actions for a simultaneous tracking of flight path and speed targets. To provide the possibility for accurate anticipatory control, quickened symbology is added to the display format. The level of detail of the conceptual design was increased by means of a participative design approach. This paper describes the design iterations that resulted in the current format.

INTRODUCTION

Navigation capabilities of future aircraft will become more and more complex. Aircraft will be expected to fly precise 4-D routes. Automatic Flight Control Systems (AFCS) are needed to automatically fly a 4-D route. Navigation and guidance displays must provide the pilot with information about the performance of the system, relative to the constraint imposed by economy and safety. The aim of the display format is to convey the needed information while minimizing the required effort for interpretation and evaluation, both for automatic and manual controlled flight.

The Energy Management Primary Flight Display (EMPFD) is a guidance and control display, which provides information on which control to use, to satisfy both flight path and speed control objectives simultaneously. It is based on the Total Energy Control principles which are also used in the Total Energy Control System (TECS) [refs. 1 and 2].

The conceptual design was performed by A.A. Lambregts, and was provided as a set of drawings. Visualization of energy relations poses significant constraints on the degrees of freedom that are available in display format design. The likelihood of detecting conflicting design requirements increases significantly when a dynamic prototype of the conceptual design is available. In the remainder of this paper, it is described how a more detailed specification of the constraints, together with feedback from domain experts, has been used to increase the level of detail of design. Key to the evolution from the static conceptual design to the current implementation, was the possibility to have a dynamic prototype integrated with a simulation environment at every phase in between. The lessons learned during the design process are summarized in the conclusions and recommendations.

BACKGROUND

The crash of the A330 at Toulouse [ref. 3] is a typical example of lack of energy awareness. The Airbus Industrie A330 which crashed at Toulouse during a test flight, lost directional control when its speed dropped dramatically after it was pitched up under autopilot control. "The absence of pitch limit protection in the autopilot's altitude acquisition mode played a decisive role in the accident"

The key factors cited by the investigators were:

- selection of a 2000 ft altitude autopilot setting on autopilot
- selection of maximum power after the left engine's throttle was reduced to idle as part of the test, asymmetric power conditions became extreme.
- engagement of the improperly set autopilot 6 seconds after takeoff. pitch was 25 degrees while speed decreased to 145 knots
- speed decreased to 100 knots at 19 seconds after takeoff, where autopilot is disconnected
- alpha-floor system started winding up the left engine
- alpha-floor was overridden by throtteling back right engine, and pushed fully forward on side-stick
- speed dropped well below the minimum control

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speed with maximum asymmetric power of 118 knots leading to loss of control

At engagement of the improperly set autopilot, the crew should have noticed that the autopilot made control actions that were not feasible with the current energy state. The autopilot commanded the aircraft beyond the flight envelope constraints (see fig. 1).

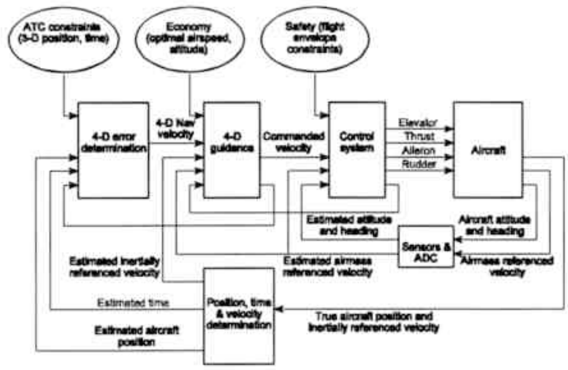

Fig. 1. Generic description of a 4-D navigation system. To perform 4-D guidance, the system must control the velocity and the direction of flight to ensure that the future desired position and velocity match the desired position and velocity within certain predefined margins. Due to the available margins, a set of guidance solutions exist. The function control system uses the airmass referenced velocity provided by the air data computer (ADC) and the attitude and heading to keep the aircraft within a safe flight envelope. It uses the direction and magnitude of the commanded velocity to keep the aircraft within the allowed margins specified by Air Traffic Control (ATC). A feedback loop from the control system to the 4-D guidance system is used to signal situations in which the commanded velocity would conflict with the velocity needed to remain within a safe flight envelope.

A 4-D navigation system is visualized in figure 1. To meet the navigation goals, guidance is needed. "*Guidance is the determination of a trajectory from a current position and velocity to a desired position and velocity, satisfying specified costs and constraints.*" [ref. 4] Part of these constraints are energy constraints. Energy state awareness therefore is needed to guide the aircraft safely along the 4-D trajectory.

Studies have been performed into the influence of future navigation concepts. Some aspects of those influences, found in reference 5, are reproduced here. See also figure 2 for the relative relations between the terms used here.

The future Air Traffic Management (ATM) system takes advantage of area navigation capabilities of future navigation and surveillance systems. These systems will locate the airborne aircraft improved accuracy and will allow for tighter spacing. Aircraft will be expected to fly precise 4-D paths and profiles to maintain a conflict-free flight. To achieve this, the flight crew-aircraft combination must have the ability to maintain an assigned vertical and lateral path, and to cross a designated fix within an assigned time window. To meet these requirements, future aircraft will need to have advanced Automatic Flight Control Systems (AFCS), which will allow progressively more complex flight paths and profiles to be flown automatically. These AFCS's must allow the pilot to quickly take over manual control of the aircraft, if the situation calls for it.

Therefore, the flight crew must maintain a adequate level of system awareness at all times. In order to maintain flight safety, they must be able to interpret *how* and *why* the manual or the automatic controlled aircraft is responding as it does. Therefore, navigation and guidance displays are needed that convey all the needed information, require a minimum effort for interpretation and evaluation, and minimize the likelihood of mis-interpretation. If the crew decides to intervene with the automated system, the displays must provide the crew with the data necessary to manually control the aircraft with effectively the same operational capability in terms of performance. Since most of the time situations that require a pilot to intervene increase pilot workload, no switching between different display types should occur in this kind of situations [ref. 6]. Therefore, a display format should provide information in a way that it can be used both for supervisory and manual control.

Regarding navigation and guidance displays Theunissen [ref. 4 p. 11] states: '*To avoid that future developments impair safety, better navigation and guidance displays must be developed which require less effort from the pilot to stay on top and ahead of the situation. To reduce the sudden built-up of task demanding load, displays should provide information which enables pilots to operate in an open-loop mode allowing anticipation of future events.*'

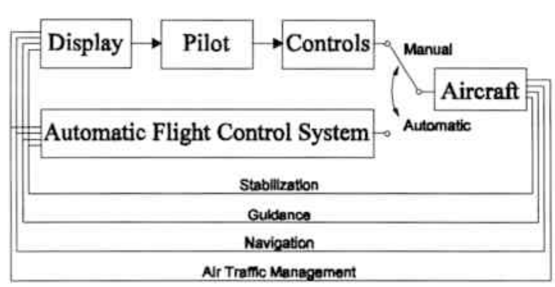

Fig. 2. Survey of the relation between stabilization, guidance, navigation and air traffic management from innerloop to outerloop.

Current situation

In the current situation, pilots are trained to use an open-loop control strategy. As a result of extensive training, they know how to set throttle positions for certain FPA and speed combinations open-loop. By watching how the system reacts, they tune the throttle position for the desired speed and FPA combination. To compensate for the large system latency involved here, several Primary Flight Displays include a speed trend vector, namely The Fokker 100 [ref. 8], the Boeing 747-400 [ref. 9], the MD-11 [ref. 10] and others. This speed trend vector works well for tuning the throttle in case of a constant FPA. In case of a changing FPA, thrust also has to be tuned for the FPA. The speed trend vector is in fact a single-input / single-output (SISO) solution to a multi-input / multi-output (MIMO) system. This SISO approach is often seen in AFCS [ref. 7], where it can work well if the other parameters remain unchanged. But speed and FPA influence each other, so in fact they will never stay constant if one is changed and nothing is done to correct the other. To compensate for the coupled SISO problem, a MIMO AFCS was developed using Total Energy Control principles. This system is referred to as the Total Energy Control System (TECS) [refs. 1 and 2].

Using Total Energy Control Principles

Lambregts [ref. 11] describes TECS as follows: '*The TECS design uses thrust to control total energy and the elevator to control energy distribution, to satisfy flight path and speed targets. The result is a pilot-like, energy efficient operation. The operation is directly compatible with the flight path angle/potential flight path angle display of an HUD system.*' So the strategy used by this pilot-like operating AFCS can be visualized by making use of a flight path angle (FPA) and potential flight path angle (PFPA). Putting these symbols onto the Primary Flight Display (PFD) was already mentioned by Baty [ref. 12] in 1976.

It is expected, that by depicting the energy relations on the PFD, the actions of TECS will become more transparent to the pilot, and probably will also make it a very good display for supervisory control.

Display quickening

Visualization of the energy relations will not always be enough for the accurate timing and magnitude of an open-loop control action. Lags are involved for flight path angle, altitude and speed response. These lags are too large for the pilot to successfully close the path and speed tracking loop with a high gain. Therefore, the interim (innerloop) control variables pitch attitude and speed trend vector are used to help closing the outer loop. These interim variables provide the pilot with a higher control bandwidth, but are also influenced by system latencies. Various studies have demonstrated the benefit of predictive and quickened display symbology with respect to pilot workload and task performance when system latency is involved [ref. 13, 14, 15 and 16]. From these studies it can be concluded that prediction and quickening provide lead compensation to help the pilot compensate for the effects of system latency. Compensating for the system latency will result in overall improvement in performance, more homogeneous performance between pilots and between conditions, and reduced control activity.

The DELPHINS II simulator

In June 1990, DELPHINS (The Delft Program for Hybridized Instrumentation and Navigation Systems) was initiated at the Delft University of Technology, The main goal of this program is to develop suitable presention methods for four-dimentional navigation and guidance information, which can be used during the manual and the supervisore control task.

The DELPHINS II part-task simulator is used for preliminary display format evaluation. It consists of three personal computers that all provide one flat-panel LCD screen with display information. To control the simulated aircraft, there is available: an force-feedback stick, a two lever throttle box for separate control of left and right engines and a rudder pedal. For generation of the graphics, the DELPHINS Display Design System (D^3S) [ref. 17] software is used. This software makes it easy to create and change display formats. There was a aircraft simulator model operating on the system, but it was lacking in level-of-detail.

IMPROVEMENT OF PART-TASK SIMULATOR

In view of the energy based principles of the EMPFD, the flight simulator requires a sufficiently realistic model to evaluate the display. The existing flight model was a simple point-mass based model. Airspeed was only dependent on throttle position and attitude was only dependent on stick inputs. No energy relations were used.

The Total Energy Control principle is based on proper control of the energy state and control of the distribution of it between potential and kinetic energy. The model's energy sources and losses and the inertial quantities related to energy have to be realistic. The power plant of the aircraft is an internal energy source, which provides thrust. Not only thrust, but all the internal forces determine the change in the energy state. The internal forces thrust, lift, drag and weight are applied on the aircraft inertia. Their dependence on aircraft parameters, atmosphere parameters, speed and attitude should be taken into account. The attitude of the aircraft is manually controlled by the stick input, so dynamics for attitude control by stick is a necessity.

Because the aircraft is moving relatively to the surrounding air, energy can be added or retracted from the aircraft energy state in a disturbed atmosphere by change in movement of air mass. This form of external energy exchange will not be implemented.

Requirements for modelling approach

The aircraft and engine model will be integrated with the DELPHINS II simulator. With this simulator, other researchers also perform display evaluations. The present and future experiments require an aircraft model to simulate flight. In future experiments this model may have to be expanded or changed. In the setup of the model these possibilities should be considered. Requirements for these possibilities are specified as follows:

- To enable easy reuse by other people, the aircraft and engine model should be generic
- It should be a well-organized model, which provides a clear view of the underlaying algorithm.
- There should be good possibilities for verification and evaluation of the model without usage of the DELPHINS II simulator.
- Small adaptation of the model structure should be flexible.
- For the uniformity, the model should be written in C-code. In this way, it can easily be appended onto the current DELPHINS II simulator code.
- Model parameters can be changed in a few seconds without compilation of the total source code.

Approach chosen for modelling

The above presented requirements ask for a design tool and not just code maintenance. In a design tool a clear view of the model will be possible, if the model is presented like a block model. This will make it easy to change the model design. The tool needs a simulator for evaluation inside, and a C-code generator to translate the model structure into code. A tool satisfying all these possibilities is Matlab Simulink. This is also a tool which is known by the students who will have to use it if they want to change the model structure.

With Matlab Simulink it is very easy to generate, alter and simulate a mathematical model. After completion of the model, the Real Time Workshop can generate C-code from the mathematical model. This C-code is generated to run in a stand alone executable, so an interface has to be made between the model code and the rest of the DELPHINS II simulator code to communicate (see fig. 3).

Flexible change of the model parameters can be produced by a parameter initialization file. This is provided in Matlab Simulink, but once the code is generated, it is only possible to use standard parameters or download them from a running Matlab Simulink program. This will not be tolerated by the requirements, so C-code has to be written manually to read a parameter file and initialize the model. Using a parameter initialization file is very common in the DELPHINS II simulator code.

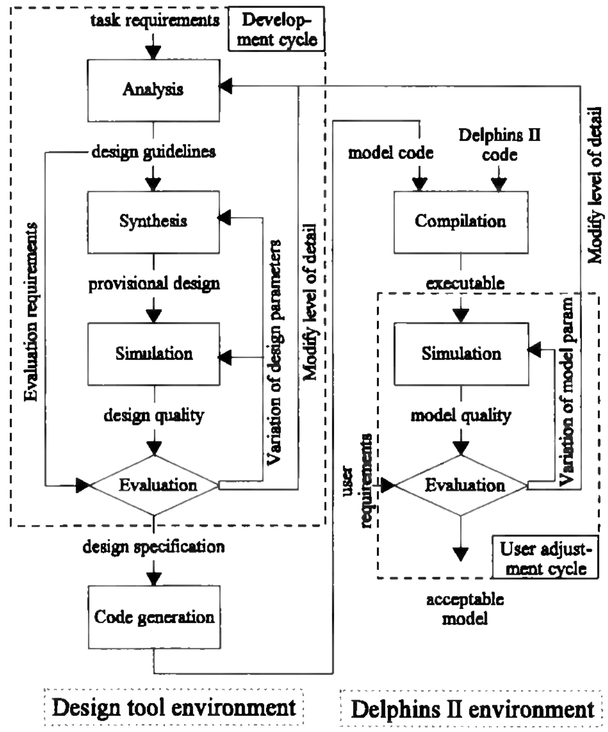

Fig. 3. Structure of the modelling approach. Design tool is used for the development cycle and a model parameter adjustment file is used for the user adjustment cycle.

Aircraft model design

The aircraft model is generated from classical flight dynamics and standard inertial equations. Equations and principles are used from references 18, 19 and 24. The model parameters are set to simulate a Fokker F-28 Mk 1000 with two Rolls Royce Spey Mk 555 mixed flow turbofan engines. A detailed description of the aircraft and engine models can be found in appendix A and **B** respectively.

OBJECTIVES AND REQUIREMENTS FOR THE ENERGY MANAGEMENT PFD

The objectives of the Energy Management PFD are to apply display technology to:

- reduce pilot workload during manual aircraft control
- simplify execution of complex terminal area maneuvers
- improve manual control accuracy
- improve insight in TECS for monitoring
- get energy efficient thrust control
- get more homogeneous performance between pilots

The general idea to accomplish this, is to simplify the control of the underlying MIMO system. The MIMO control laws of the TECS system make it possible to achieve decoupled command responses. To satisfy flight path and speed targets, it uses thrust to control total energy and the elevator to control energy distribution. To get this decoupling of the thrust and elevator in case of manual control, the underlying MIMO system has to be visualized as two (related) SISO systems. A requirement for this approach is, that both SISO systems are easy to control with the feedback provided. This feedback is determined by the display format.

The state of the MIMO system has to be indicated by a geometric relationship between the symbols representing the state of the two SISO systems. The first system, mainly dependent on thrust, visualizes the nett amount of available energy change per unit of time, which is symbolised by the PFPA. The second system, mainly dependent on elevator input, is the distribution of this available energy rate. Elevator input balances the distribution of energy between the acceleration and vertical speed. This balance has to be visualized by the display format.

DISPLAY EVOLUTION AND CONSTRAINTS

Original Energy Management Flight Control Display

In figure 4, the original Energy Management Flight Control Display (EMFCD) is shown. This concept drawing is made by Lambregts (FAA), who is the founder of this display. This FCD is not a Primary Flight Display (PFD) and is not supposed to be used like a PFD. Because this EMFCD is the basis for the EMPFD, it will be briefly discussed.

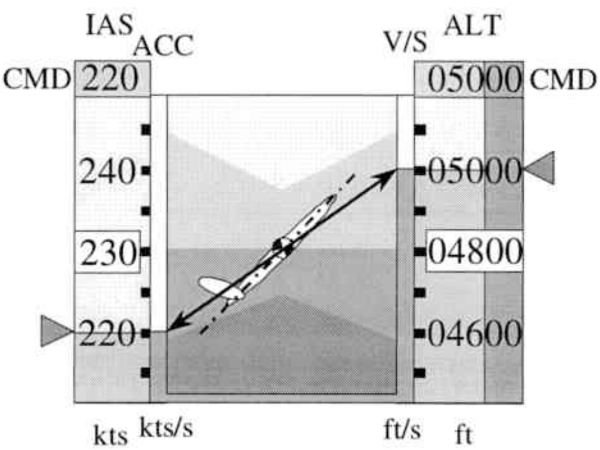

Fig. 4. Original Energy Management Flight Control Display as suggested by Lambregts

The EMFCD has an indicated airspeed (IAS) tape on the left side and an altitude tape on the right side. Airspeed is displayed in knots and altitude is displayed in feet. On the centre of the tapes the actual airspeed and altitude are displayed in a small box. The commanded airspeed is displayed on the top of the speed tape in a separate box and left of the tape there is also an arrow pointing at the commanded speed. The same concerns the commanded altitude, but then of course mirrored. To the right of the speed tape, an acceleration tape is displayed with a scale in knots per second. To the left of the altitude tape, a vertical speed tape is displayed with a scale in feet per second. The scale indicators are not visible in this sketch of the EMFCD but other sketches do have a scale indicator with digits, which obviously needs more display area.

The acceleration and vertical speed tape are connected by a tube on the bottom of the display. The idea is that the speed tape, the tube and the vertical speed tape form a U-shaped tube which contains a fluid. The total amount of fluid is comparable to the total available energy rate which can be divided between either acceleration or vertical speed.

On the inside of the display an arrow points at the current acceleration and the current vertical speed. This arrow also shows the condition of power distribution between the acceleration and vertical speed. Therefore, it is called the distribution vector. Because the available power is bounded between a lower limit and an upper limit, the distribution vector is only able to move in a certain area. This area is visible as the lying hourglass shaped planes in the middle of the display. From this area, the available performance of the aircraft is visible.

Summarising, the EMFCD is a control display which shows the pilot the current energy state in terms of kinetic and potential energy, and their rate of change.

From Flight Control Display to Primary Flight Display

The information displayed on the FCD gives the pilot more insight in guidance and control of the aircraft. This information should not be displayed on a separate display if the information could be integrated with the other control and guidance data. Distribution of data presentation obliges pilots to scan, which means time loss and an increase in workload. The control and guidance display already present in the cockpit, is the PFD. The goal of the design effort is to integrate the energy management information in the PFD. The energy management information will impose constraints on the display format of the PFD.

Energy Management constraints

The aim of the energy state visualization is to provide a clear indication of the current energy state, so the pilot can extrapolate future events from it, which he can use to coordinate his control actions. To allow the pilot to obtain a qualitative estimate of the energy balance, without having to perform mental scaling operations, all indications of energy should use the same scaling factors. To achieve this, energy in terms of energy per unit of length should be the same for both kinetic and potential energy. This also concerns the rates of change of energy, which are visualized by acceleration and vertical speed. Energy and energy rate should therefore have a constant relation. The main relation to be displayed is the distribution of the total energy rate between acceleration $\dot{V}$ and vertical speed $\dot{h}$. This relation derived by Lambregts [ref. 11] is:

$$\dot{E}_{S_N} = \gamma_p = \gamma + \frac{\dot{V}}{g} = \frac{\dot{h}}{V} + \frac{\dot{V}}{g} \quad , \qquad (1)$$

where $\dot{E}_{S_N}$ is the non-dimensional specific total energy rate of the aircraft, which is visualized by the potential flight path angle γ_p in relation to the flight path angle γ. The acceleration of gravity is g and V is the true airspeed. The PFPA is displayed between the acceleration and the vertical speed, but it is the sum of both the energy rates. Dividing the PFPA by two will visualize the average energy rate, which of course is right in between the energy rate of the acceleration and vertical speed. So, if scaling factors, references and distances between the parameters are correct, then visualizing this equation will result in a straight line through the PFPA distributing energy between acceleration and vertical speed (see fig. 4 and 5).

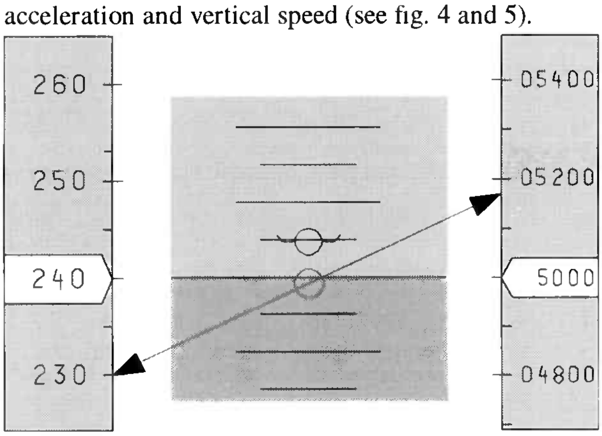

Fig. 5. First format of Energy Management PFD. With distribution vector displayed as arrow between acceleration and vertical speed. The centre of the arrow is the PFPA displayed as circle. Above that in the centre of the display, is the current FPA.

From equation 1, it can be concluded that there is a constant scaling factor between acceleration and PFPA and there is a variable scaling factor between the vertical speed and the PFPA. This variable scaling factor is dependant on the current airspeed V. Acceleration, PFPA, and vertical speed should still be displayed in their normal quantities, therefore their indicator scales should be scaled with the scaling parameters. Scaling of the pitch reference scale (reference for the PFPA) will be dangerous, because then a quick-glance interpretation of the attitude of the aircraft will not be possible due to a variable angle over length ratio on the display. This means that the vertical speed tape should be scaled inversely proportional to the current airspeed V. If a constant time relation between vertical speed and altitude needs to be maintained, then the altitude tape should also be scaled inversely proportional to the current airspeed. This same time relation should also be used between acceleration and speed. If done so, the speed and altitude tapes should display an equal amount of energy per unit of length on the display.

To verify this, the kinetic energy and potential energy can be written as

$$\tfrac{1}{2} m V^2 = m g h \quad , \qquad (2)$$

where m is the mass, V is true airspeed, h is the altitude and g is the acceleration of gravity. The above equation can be written in differential form. This equation will provide us the relation between an equal amount of energy rate between acceleration $\dot{V}$ and vertical speed $\dot{h}$:

$$V \cdot \dot{V} = g \cdot \dot{h} \, . \qquad (3)$$

For small perturbations the incremental form will be

$$\Delta V = \frac{g}{V} \Delta h \qquad (4)$$

From equation 4 can also be concluded that a height difference Δh should be scaled with a scaling factor that is inversely proportional to speed V to get the speed difference ΔV which presents the same amount of energy.

The only parameter still free to be chosen, is the time constant between acceleration and speed, and between vertical speed and altitude. This time constant determines the scaling factor between the energy tapes and energy rate tapes. It represents the time it would take to change the speed or altitude with a certain scale length if the acceleration or vertical speed has the same constant scale length. So if the time constant is set at 10 seconds, the scale length representing 20 knots on the speed tape is the same as the scale length representing 2 knots/s on the acceleration tape. A time constant of 10 seconds has proven to be useful for speed tape displays in PFDs. The Fokker 100 Aircraft Operation Manual [ref. 8 section 1.17.01 p. 10] tells their magenta speed trend vector: "*indicates the predicted airspeed within ten seconds.*" The Boeing 747-400 manual [ref. 9 p. 3-102] tells: "*A speed trend arrow extends up or down from the point of the CAS readout box to indicate airmass referenced acceleration. The arrow length is scaled so that the tip indicates the predicted airspeed in ten seconds.*" In the MD-11 Cockpit Pilot's Guide [ref. 10 p. 2-17] is mentioned: "*A green trend vector, originating from the current speed proportional to acceleration, indicates the speed attained after 10 seconds.*"

Because of the relations between speed, acceleration, PFPA, vertical speed, and altitude, the references of their tapes should be fixed relatively to each other. In other words the references of the tapes should all be lined up with the horizon.

Artificial Horizon Indicator symbols

The first format of the EMPFD (see fig. 5) looked a lot like the format of the EMFCD, but then of course with an Artificial Horizon Indicator at the centre of the display. On the artificial horizon there are scale markings for pitch reference. At this phase of the development the angle indication scale is a reference for the FPA and PFPA symbols. An attitude symbol was not yet necessary for evaluation of the concept.

In some of the present-day cockpit displays an FPA is already displayed and sometimes it is accompanied with the PFPA. The Flight Dynamics Head-Up Guidance System (HGS) [ref. 20 p. 8 - 10] has a flight path symbol, which *"provides an instantaneous and continually updated indication of where the aircraft is going through space"* and a flight path acceleration symbol, which " *indicates the acceleration (or deceleration) of the aircraft along the flight path.*" Flight path acceleration and PFPA are equal. Putting these symbols into the PFD was already proposed in 1979 by Baty [ref. 12]. The FPA symbol displays the direction of flight and the PFPA symbol displays the direction of flight that can be flown with the current throttle setting and with the current constant airspeed. So, if the FPA is put on the PFPA, speed will stay constant. The PFPA can be used to determine the power that is needed to fly the aircraft at the current FPA with current airspeed. The angle between the FPA and the PFPA is an indication of the current acceleration or deceleration, and can therefore be used to tune the throttle setting for current FPA with current airspeed. Even pitch maneuvers can be coordinated with throttle movements by keeping the two indicators together.

Command target symbols

The commands should be visible on the guidance display so the pilot is able to see his deviation from and direction to the commanded target. On the Fokker 100 PFD [ref. 8 section 1.17.01 p. 14] a pointer including numerals is used to annunciate the selected altitude. The Boeing 747-400 [ref. 9 p. 3-100] and the MD-11 [ref. 10 p 2-17] use bugs, which are displayed on the matching place on the tape. The control actions should be based on the positions on the tape of the commanded targets. Therefore, the visualisation of the commanded targets should be clear. The striking pointer with numerals is clearer than the small bug, and therefore is used in the EMPFD. The FPA target symbol is a green circle, which fits exactly in the FPA symbol. On engagement of the new commands the pointers and target FPA symbol will move to their new position. The current command symbols and command mode annunciators from the Mode Annunciator Panel (MAP) (see appendix C) are the only indicators that are displayed in green to group them and separate them from the other symbols (see fig. 6).

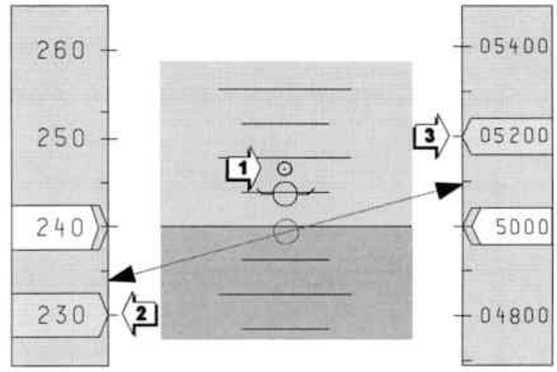

Fig. 6. Second concept of EMPFD with added target symbols and bugs.
1. *Target flight path angle symbol (green)*
2. *Target speed bug (green)*
3. *Target altitude bug (green)*

IMPROVEMENTS DUE TO INITIAL EVALUATIONS

The display format presented by figure 4, is in principle the concept drawing of the EMFCD modified at the inner display to get a PFD format. From this format the development began to a more fully-developed PFD. The original concept drawings were the only available information to start with. In these static drawings, a lot of design requirements kept hidden. By dynamic simulations new dependencies were revealed and conflicting design requirements were identified. The dynamic simulation of the concept display formats were performed on the DELPHINS II real-time part-task simulator. Three display screens are available. One is used for engine instruments, which leaves the other two screens for displaying two different EMPFDs simultaneously. For instance one screen showing the new format and one showing the old one. This is a great tool to visualize the differences and improvements. The evaluation of the development process had an iterative nature. The existing symbols and conventions were used, but if needed there was deviated from it. The iterative process resulted in the following changes of the display format.

Changing distribution vector format and adding attitude indication

After experimenting with the first format of the EMPFD, an collective criticism was expressed about the distribution vector. A change in energy balance causes a rotation of the distribution vector which tens to induce a sensation of a change in roll angle. To change energy distribution a longitudinal stick is generated, but to roll the aircraft, a lateral stick movement is needed. The reason for this confusion is the size of the distribution vector. The distribution vector is longer than the artificial horizon. This results in a vicious mix-up between the distribution vector and the artificial horizon. The only solution to this problem is removing the line connecting the acceleration bug, the PFPA symbol and the vertical speed bug (see fig. 7).

Addition of attitude symbol

Addition of the attitude symbol is needed for aircraft stabilization and other in flight tasks that demand attitude information like unusual attitudes, landing, etc. From this point of view it is inevitable to display a attitude symbol.

Inside-out versus outside-in

As already learned from the energy management constraints, the altitude and speed scale references should be fixed to the horizon, because then the energy errors are displayed relatively to the PFPA. Usually the altitude and speed scale references are at the centre of the tapes. Keeping them at the centre implies that an outside-in frame of reference must be used. This means the horizon is fixed and the attitude symbol rolls right and left, and pitches up and down. To prevent the aircraft symbol from going off scale, the complete pitch range must be visible, but the resolution requirements of the scale should also be met. These combined requirements will result in a too large display.

An inside-out frame of reference will have moving references of the tapes. Situations with extreme attitudes result in clipping of the reference pointers to the end of the scale. In case of clipping energy management will not be possible. In a compare between the both formats Theunissen [ref. 4 p. 114] concluded: "*When the navigation task requires relative navigational awareness, an inside-out frame of reference should be used.*" The outside-in frame of reference has a better absolute navigational awareness, which for instance is needed in case of unusual attitudes, where a clear view of the situation is needed to maneuver the aircraft to a safe attitude. Unusual attitudes should never occur. This is why an alpha margin indicator [ref. 8 section 1.17.01 p.18] or a pitch limit indicator [ref. 10 p. 2-50] is used. Because relative navigational awareness is required by the tasks, and unusual attitudes can be prevented by pitch limiters, the inside-out frame of reference should be used.

Velocity vector aligned versus attitude aligned

Using a velocity vector aligned display (see fig. 5 and 6) is the most obvious, since all the energy relations are related to a FPA (velocity vector). If the FPA is zero, the horizon and all the scale references will be on the centre of the display and potential energy will be constant. In a velocity vector aligned display, both the artificial horizon and the attitude symbol move. The angle between the artificial horizon and the attitude symbol are used for stabilization. This is a compensatory task, which will have negative effect on the inner-loop stabilization. In an attitude aligned frame of reference display, the artificial horizon will move relatively to the fixed attitude symbol. This is a pursuit task and will therefore have a better inner-loop stabilization. Since the display is not designed for a specific Flight Control System (FCS) and stabilization of the aircraft should be possible with the display, the attitude aligned frame of reference should be used.

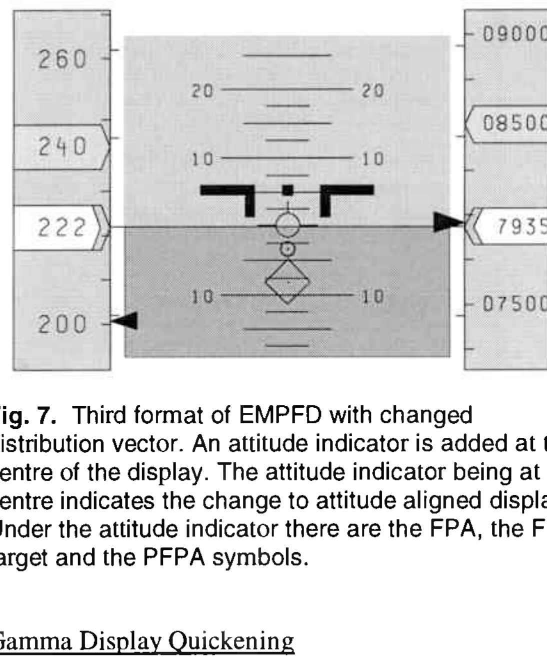

Fig. 7. Third format of EMPFD with changed distribution vector. An attitude indicator is added at the centre of the display. The attitude indicator being at the centre indicates the change to attitude aligned display. Under the attitude indicator there are the FPA, the FPA target and the PFPA symbols.

Gamma Display Quickening

The FPA presented on the display is used for guidance, especially in a FPA task. Evaluation experiments showed control handling problems. From Lambregts et al. [ref. 16] was learned that the pilot control handling problems, experienced with the response lag of the displayed FPA, could be overcome by addition of a virtually lag free FPA command display. A command display is not possible in this case because there is no augmentated Flight Control System (FCS), but quickening can be used to calculate a estimated lag-free FPA. This quickened FPA symbol, will have a transient response that looks like pitch and a true FPA indication with the controls at neutral. Different display formats were tried for the quickened symbol. A separate symbol was confusing and cluttering. An arrow pointing from the current FPA to the position of the quickened FPA is more intuitive, but also less striking.

The quickened FPA is obtained by adding the high frequency component of the pitch θ to the true FPA γ. This can be achieved by making use of a first order washout filter with time constant τ_γ. This washout filter was derived by D. Bray (see appendix D) and results in the quickened flight path angle:

$$\gamma_{\text{quickened}} = \gamma + \frac{\tau_\gamma s}{1+\tau_\gamma s} \cdot \theta \tag{5}$$

The time constant τ_γ is determined experimentally with use of Matlab Simulink and the DELPHINS II simulator. The experiment results showed a dependance of the speed which can be approximated by the function

$$\tau_\gamma = 45 \cdot V^{-0.85} \tag{6}$$

for this flight model (see fig. 8).

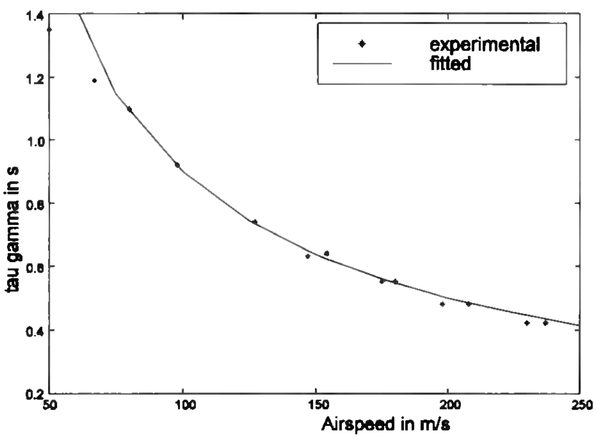

Fig. 8. Dependance of speed to the time constant τ_γ is shown. The experimentally obtained results are fitted by a function.

Quickening of potential FPA

From the point mass aircraft equations of motion it follows that

$$T_{\text{required}} = W \cdot (\sin \gamma + \tfrac{\dot{V}}{g}) + D \tag{7}$$

were $T_{required}$ is the required thrust that is needed to fly with a flight path angle γ and an acceleration $\dot{V}$, if drag *is D* and weight is W. The acceleration of gravity is g. Assuming that γ is small the incremental thrust required is:

$$\Delta T_{\text{required}} = W \cdot (\Delta\gamma + \Delta\tfrac{\dot{V}}{g}) + \Delta D \ . \tag{8}$$

TECS now assumes that drag is constant for a specified flight condition. So the classic TECS core structure is defined by

$$\Delta T_{\text{required}} = W \cdot (\Delta\gamma + \Delta\tfrac{\dot{V}}{g}) \ . \tag{9}$$

Kurdjukov et al. [ref. 21] discussed the problems of this assumption and added a correction term for the drag variation. The result is the Modified Energy Control System (MECS) which has demonstrated a substantial improvement with regard to atmospheric disturbance rejection. MECS uses the drag coefficient C_D for calculating of drag variations, where C_D is dependent on the main variables speed V, thrust T and angle-of-attack α:

$$\Delta D = q \cdot S \cdot \Delta C_D (V, T, \alpha) \tag{10}$$

where q is the dynamic pressure and S is the wing area. To calculate the differences in the drag coefficient, the linear Taylor series expansion is used:

$$\Delta C_D = (C_D^V \Delta V + C_D^T \Delta T + C_D^\alpha \Delta\alpha) \ . \tag{11}$$

The aerodynamic coefficient slopes C_D^V, C_D^T and C_D^α are aircraft dependent so they should be determined experimentally or from the aircraft aerodynamic data base. The differential parameters are also difficult to measure, especially the thrust.

For the display ,another approach can be used that is not aircraft dependent. During a pitch maneuver drag will change temporarily due to a transient angle-of-attack. Because the PFPA is calculated from

$$\gamma_p = \sin \gamma + \tfrac{\dot{V}}{g} = \tfrac{T-D}{W} \ , \tag{12}$$

a drag variation ΔD leads to a inaccurate PFPA indication of

$$\gamma_p = \tfrac{T-(D+\Delta D)}{W} = \tfrac{T-D}{W} - \tfrac{\Delta D}{W} \ , \tag{13}$$

The PFPA normally doesn't have any high bandwidth changes, because weight, thrust and drag don't have big changes in short time periods. In case of a pitch maneuver there is a relative large change in drag over a small period of time. So if this high bandwidth change of drag, could be filtered from the change in PFPA, then the drag variation will have less influence on the PFPA. So the change in PFPA has to be low-pass filtered during a pitch maneuver. The time constant $\tau_{\gamma p}$ of the low pass filter determines the bandwidth of the filter. This time constant must be tuned by a variable that is related to the drag variation. This variable is the change of the angle-of-attack due to the pitch maneuver $\Delta\alpha$, which is calculated by subtracting the FPA γ from the quickened FPA $\gamma_{quickened}$.

$$\Delta\alpha = \gamma_{\text{quickened}} - \gamma \tag{14}$$

So the transfer function of the low pass filter has a time constant $\tau_{\gamma p}$, which is dependant on the difference in angle-of-attack due to the pitch maneuver

$$G(s)_{\gamma_p} = \frac{s}{\tau_{\gamma_p}(\Delta\alpha)\, s + 1} \ , \tag{15}$$

and is used on the PFPA change to calculate the PFPA in case of a pitch maneuver. This results in a compensated PFPA which is stable for even quite large pitch maneuvers.

Quickening of energy distribution rate

The energy distribution rate is displayed as a compound two-dimensional vector connecting the actual acceleration along the flight path and actual vertical speed. The key feature of this vector is, that it is put together in such a way that it responds one dimensionally to elevator control input by rotating around the centre point, which is visualized by the PFPA symbol. In case elevator control input is generated, Bray gamma quickening (see appendix D) is used to get the quickened gamma $\gamma_{quickened}$. The quickened vertical speed $\dot{h}_{quickened}$ can be calculated by

$$\dot{h}_{quickened} = V \cdot \sin \gamma_{quickened} \,. \quad (16)$$

Quickening of thrust will also be added. The estimated PFPA will then be visible. Especially this quickening is very important because the time lag between throttle movement and acceleration is large. The quickened thrust will be

$$T_{quickened} = T \cdot (1 - G(s)_E) \,. \quad (17)$$

where $G(s)_E$ are the engine dynamics and T is the current thrust. With use of equation 1 and 12 the quickened specific total energy rate is calculated by

$$\dot{E}_{S_N\ quickened} = \frac{\dot{h}_{quickened}}{V} + \frac{\dot{V}}{g} + \frac{T_{quickened} \cdot (1 - G(s)_E)}{W} \,. (18)$$

Because of the change in drag during the pitch movement, it is difficult to estimate the quickened acceleration. By using the fact that the total energy rate is the sum of both the other energy rates, the quickened acceleration can be calculated from the quickened specific total energy rate by

$$\dot{V}_{quickened} = (\dot{E}_{S_N\ quickened} - \dot{h}_{quickened} / V) \cdot g \,. \quad (19)$$

Quickening of the energy distribution rate for pitching is only functional for high pitch rate maneuvers, otherwise the difference between γ and $\gamma_{quickened}$ will be very small, and no difference will be seen in the quickened parameters.

Certification constraints

In AC25-11 [ref. 22 p.20-22] the visual display characteristics for jet transport category aircraft are stated as: '*The minimum visible airspeed scale length found acceptable has been 80 knots. The combination of altimeter scale length and markings should be adequate to allow sufficient resolution for precise manual altitude tracking in level flight, as well as enough scale length and markings to reinforce the pilot's sense of altitude and to allow sufficient look-ahead room to adequately predict and accomplish level-off. The pitch attitude display scaling should be such that during normal maneuvers (such as takeoff at high thrust-to-weight ratios) the horizon remains visible in the display with at least 5 degrees pitch margin available.*'

If the airspeed scale length constrain is met, this will automatically determine the length of the altitude scale due to the fact that both tapes have a same amount of energy per unit of length (see energy management constraints). The scaling of the altitude and vertical speed tape inversely proportional to airspeed, is a positive incidental circumstance. At low speed, vertical speeds will also be small and resolution of the vertical speed will be high. This will be most convenient for the approach. At high speed, a large range is available, but the resolution will be less. Keeping the time constant between the acceleration and speed tape, and between the vertical speed and altitude tape at 10 seconds, this will result in a display satisfying the preceding constraints.

Also mentioned in AC25-11 [ref. 22] are the constraints for scale graduations, namely: '*Airspeed scale graduations found to be acceptable have been in 5-knot increments with graduations labelled at 20 knot intervals. Minimum altimeter graduations should be in 100-foot increments with a present value readout.*' These scale graduations are added to meet the constraints.

Another constraint from AC25-11 [ref. 22] is: '*Speed, altitude, or vertical rate trend indicators should have appropriate hysteresis and damping to be useful and non-distracting.*' This constraint makes direct quickening of acceleration and vertical speed symbols impossible. If quickening of the symbols is displayed, it should be done with separate trend vectors from the symbols or with separate symbols. The last option is implemented (see fig. 9).

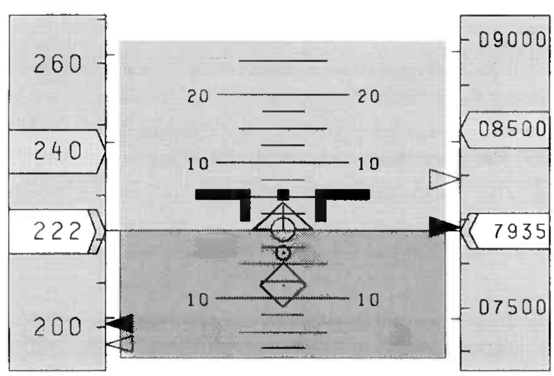

Fig. 9. Fourth concept of EMPFD with display quickening. Open bugs for quickened acceleration and quickened vertical speed are added to concerned tape. Also added is quickening for the FPA symbol. An arrow grows from the symbol to the position of the quickened FPA at pitch maneuvers.

EXPERIMENT EVALUATION RESULTS

Some of the changes which followed from initial evaluation were already discussed in the previous chapter. From evaluation with test pilots and other pilots who criticized the display, other changes in the display format were made. These changes and other valuable information coming from the experiments with the pilots will be discussed in this chapter, but first the experiment setup is discussed

Experiment setup

The subjects were briefed on three different display formats. The first display configuration is the PFD with an attitude indicator, FPA symbol, acceleration bug and vertical speed bug. The reference points of the tapes do not move together with the horizon and the altitude and vertical speed tape do not scale. There is no PFPA visualized. To show energy management relations, display configuration 2 has moving tape references and scaling tapes and a distribution vector. This configuration does not have any form of quickening, so it will only display the actual values. Display configuration 3 visualizes the fully developed EMPFD with moving tape references and scaling tapes, a distribution vector and quickened symbols.

The subjects were given the opportunity to get acquainted with the display configurations. This in some cases already brought up a deep and valuable discussion on the display format. After the acquaintance training sessions were held followed by data sessions. Afterwards the subjects were given a questionnaire with questions about the following: acceptance of aircraft model, acceptance of moving tape references and scaling tapes, acceptance of used symbology and helpfulness of it, consciousness of the displayed energy relations and perceived workload on display formats.

The subject were given combined FPA and speed commands or combined altitude and speed commands. Appendix E contains an overview of the piloting tasks that were used.

Acceptance of aircraft model

The pilots approved the aircraft model and had no problems in controlling the elevator and throttle.

Moving tape references and scaling tapes

The movement of the tape references of the four tapes gave no problem at all. Some of the pilots did not even have any notice of the change between non-moving and moving references. None of the pilots saw the scaling of the altitude and vertical speed tape as a problem. Both these results should be interpreted with care. There has been experimented with speeds between 190 and 240 knots only. The conclusion is that there are no problems detected in this speed range. Outside of this speed range experiments should be done to get a better impression of the acceptance by the pilots. Especially at low speeds, where the altitude range is small, experiments will be necessary.

Acceptance and quality of FPA symbology

The FPA was deemed to be a helpful or very helpful symbol. Initially the quickened FPA symbol was not even noticed in most cases. It was often not used by the pilots. A reason for this may be the small pitch rate which the pilots used to perform their task. A small pitch rate results in a small difference between FPA and quickened FPA. In that case quickening is not very useful.

Acceptance of the distribution vector symbology

A subject experimenting with the display configuration of figure 9 pointed out that the symbol used for the PFPA was not a well chosen symbol. "*The common symbol for PFPA is a carrot*", he said us. He had problems with the big amount of symbols presented on the attitude scale. His opinion was that the symbols cluttered because they were moving through each other.

The problem of displaying a carrot instead of a diamond is that a carrot symbol will not be centred between the acceleration and vertical speed tape. This will influence the clearness of the relation between the three parameters involving the distribution vector. The diamond was changed into a carrot, which reduced the cluttering. The difference between the diamond and the carrot in relation to the distribution vector was judging from a first impression, not of big significance. Because of the decluttering of the display which is of more significance, the carrot was kept.

The rest of the experiments were done with the carrot. The carrot itself as a symbol was no problem to the subjects anymore. Using the carrot in the right way at the right moments to perform certain tasks still gave problems. Because of the many symbols presented, there were several different strategies to handle tasks. Sometimes it was handy to use the quickened PFPA and other times the quickened acceleration bug was to be used. This was too confusing to the subjects.

One of the subjects found the PFPA symbol confusing because it is related to actual speed and not to commanded speed. This points out that this subject did not use the PFPA as a total energy rate indicator, but he expected the symbol to be a speed error indicator.

Fixation and attention

In the situation where the quickened acceleration bug is presented, it is easy to put the (quickened) acceleration bug opposite of the speed target. The disadvantage of this, is a fixation on the acceleration tape. Subjects were focussed too much on matching the acceleration opposite to the target speed, because it could be matched perfectly. In spite of this, the subjects also stated that they did not really use the quickened trend vector, because of the cluttering of the symbols. The also did not use the quickened vertical speed symbol. The complaint about fixation was not only heard in this case. The whole task was quite simple to perform, which made it a challenge to perform exactly on the target, certainly in case of having all the quickening symbols. Some of the subjects recommended to add turbulence to the tasks, which would make the task more realistic and less delicate. One of the subjects even said that the EMPFD was taking more attention than a standard PFD.

Perceived workload

From the questionnaire, speed control and setting of the throttle position appeared to be easier when energy management information is provided. If quickening of the PFPA is also added, both speed control and throttle control become even easier than without quickening.

Overview and energy relations

Most of the subjects never consciously made use of the fact that elevator control rotates the distribution vector. Subjects sometimes consciously made use of the fact that the speed and altitude tapes represent an equal amount of energy per unit of length. Comment was given that the pilot was to busy flying the aircraft to observe the energy balance in a situation with potential energy error and kinetic energy error. The display did not appear to be very intuitive and overview had not improved comparing to a standard PFD.

From these results and comments, it can be concluded that the visualization of the distribution vector and the visualization of the energy errors did not succeed to be transparent and intuitive enough to the subjects.

The opinion of the subjects about the speed and altitude trend vectors was positive. The trend vectors were seen as helpful symbols, but the visualization of them should be changed.

Acceptance of bug symbols on trend vector tapes

One of the subjects had strong comment on the bugs of the acceleration and vertical speed tape (see fig. 9). He mixed-up the bug on the inner scale to be a reference bug for the outer scale. So he thought the acceleration bug was the target speed bug for the speed tape. This is not surprising when you look at the present-day PFD. A lot of them have reference speed bugs on the tapes at almost the same position and often with the same colour.

The bugs were changed into bars originating from the scale reference point. The energy rates with this kind of visualization were much more clearly than before.

Acceptance of target bugs on altitude and speed tape

The same subject also commented the target bugs (see fig. 7). The target bugs were only separable by colour and a very small window frame. This was not enough to separate them by a blink of the eye. The movement of the current speed indicators with the references of the tapes also contributed to the confusion.

From the changing of the acceleration and the vertical speed bug, it was learned that a bar display is a very good and clearly indicator. Changing the target speed bug to a bar display could also have an intuitive representation of the relation between the outer and the inner scale.

Adding precision vertical speed scale

Another problem that came to the surface is graduations of the vertical speed scale. For certification these graduations should be on 100 ft/min increments. The scaling of the vertical speed scale being inversely proportional to the current airspeed, has the consequences of a varying resolution on this scale. This resolution is dependent on the resolution of the altitude tape and the time constant relation between the altitude tape and vertical speed tape. For low speed, the resolution will be high enough to display the 100 ft/min increments. If the speed scale length is set at 80 knots and the time constant for the trend vector is 10 seconds, the limit for displaying the increments will be around 200 knots. This means the whole approach can be flown with a precision vertical speed scale. For high speed phases of the flight, a reduced precision of the vertical speed scale will be presented having increments at 500 ft/min. The beauty of the display is the constant relation between the FPA and bar length of the vertical speed tape, being independent of the current airspeed. The question is: 'Is this wanted by the pilot.' The answers should be acquired from an experiment involving all phases of a normal flight. The results of the changes in the display configuration, which has not been evaluated yet, are visible in figure 10.

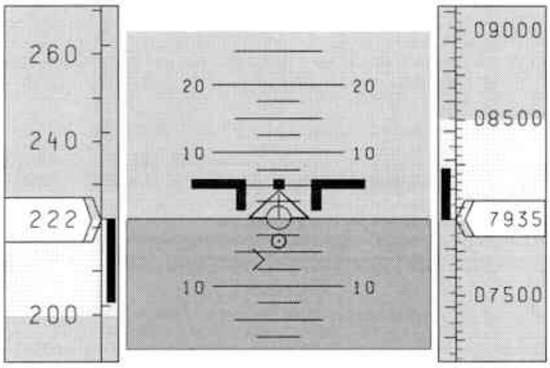

Fig. 10. Final format of EMPFD with carrot symbol instead of the diamond. Trend vectors have changed, pointers with numerals have been replaced by bars en graduation of tapes have changed.

Uncertifiable altitude trend vector

During the certification of the Fokker F-100 Electronic Flight Intrument System (EFIS), a PFD had to be certified. The PFD is shown in figure 11. This PFD was not certified because of the altitude trend vector.

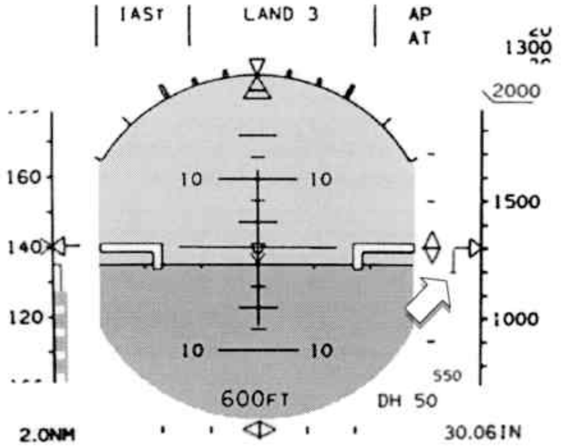

Fig. 11. Uncertifiable PFD of Fokker 100 with altitude trend vector (vertical speed indicator) left of altitude tape (indicated by arrow).

The comment for this [ref. 23] is as follows: "*The original vertical speed display could be misinterpreted. This interpretation error can arise thru relating the altitude trend vector to the glideslope scale. After all, supposing the aircraft climbs, a positive trend vector will occur. When this arrow is laid against the glideslope scale, this can be misinterpreted as a below glideslope situation. The hereto belonging instinctive reaction of the pilot is a nose up pitch command, which in this case is the wrong thing to do.*"

The glideslope indicator will be displayed on the right side of the Attitude Direction Indicator (ADI) just like the F-100 display, but it will be integrated on the inside of the ADI and not next to it. This is often seen in PFDs. The altitude trend vector will stay integrated in the tape display and will not be very close to the glideslope indicator. Integrating both objects into other objects separates them, so confusion will have been reduced to a minimum or will have been totally disappeared. Besides this, there is no FPA indication on the F-100 display, so only a relative fault is visible on the glideslope scale. With the EMPFD an open-loop action will be made to set the FPA at the desired glideslope. Looking at the FPA, the error will be immediately detected. For finetuning, the glideslope indicator comes in handy.

SUMMARY AND CONCLUSIONS

Summary

It is expected that the method of visualization described in this paper allows decoupling of the control actions for a simultaneous tracking of flight path and speed targets. It also is expected that by this method of visualization, the actions of TECS will become more transparent to the pilot, and probably will also make it a very good display for supervisory control. The aim of the energy state visualization is to provide a clear indication of the current energy state, so the pilot can extrapolate future events from it, which he can use to coordinate his control actions. The display is therefore expected to provide more insight in guidance and control of the aircraft. The objectives of the Energy Management PFD are to apply display technology to:

- Reduce pilot workload during manual aircraft control;
- simplify execution of complex terminal area maneuvers;
- improve manual control accuracy;
- improve insight in TECS for monitoring;
- get energy efficient thrust control;
- get more homogeneous performance between pilots.

These expectations assume that TECS is used for these display methods. The TECS core algorithm was visualized on the PFD, which raised questions. For lag compensation symbols were added, which again raised questions. The answers to these questions are published in this paper. More research should be done to verify the expectations posed above. The questions that raised from the visualization of TECS and addition of quickening are:

- Is movement of the tape references acceptable?
- Is scaling of the altitude and vertical speed tape a problem?
- Has been made use of the fact that elevator rotates the distribution vector around the PFPA symbol?
- Has been made use of the fact that speed and altitude are displayed in terms of equal amount of energy on the tapes?
- Is the FPA symbol helpful and is the visualization of it acceptable?
- Is the quickened FPA symbol helpful and is the visualization of it acceptable?
- Is the PFPA symbol helpful and is the visualization of it acceptable?
- Is the quickened PFPA symbol helpful and is the visualization of it acceptable?
- Is the acceleration indication helpful and is the visualization of it acceptable?
- Is the quickened acceleration indication helpful and is the visualization of it acceptable?
- Is the vertical speed indication helpful and is the visualization of it acceptable?
- Is the perceived workload influenced by visualization of the above symbols?

The questions listed above have been addressed by means of evaluations. Appendix E contains an overview of the piloting tasks that were used. These evaluations let to the following findings:

- Movement of the tape references was not perceived as a problem;
- scaling of the altitude and vertical speed tape was not perceived as a problem;
- FPA symbol is helpful;
- quickended FPA symbol is not often used;
- PFPA symbol clutter with other symbols;
- usage of the PFPA symbol was not clear in al situations due to the surplus of symbols;
- the strategy of when to use quickened acceleration and when to use PFPA is unclear;
- quickened vertical speed was not used at all;
- speed control and setting of the throttle position are easier with the current visualization of energy management information;
- quickening of the PFPA makes speed control and throttle control easier;
- most of the subjects never consciously made use of the fact that elevator rotates the distribution vector;
- the relation between parameters of distribution vector is not clear enough;
- subjects in some cases consciously made use of the fact that the speed and altitude tapes represent an equal amount of energy per unit of length;
- the bugs on the trend vector tapes are confusing;
- target speed and altitude pointers with numerals are confusing with actual speed pointers because they look alike;
- graduations on vertical speed scale are missed.

These findings resulted in the following changes:

- Change of PFPA from diamond into carrot symbol;
- change of trend vectors from bugs into a bar display;
- change of target altitude and target speed pointer; with numerals into bar, which displays the potential and kinetic energy error;
- addition of a precision vertical speed scale indicator with 100 ft/min increments at low speed.

Conclusions and recommendations

The overall results are encouraging. The display developed into a format with all the required energy relations visualized. The format has been cleared from cluttering symbols. Symbols were changed if this improved the clearness of the display, and they were left out if they were not of primary significance. The final format has not been evaluated, so it is recommended to gather experimental information on this display. The most valuable information will be obtained from an experiment, which includes all phases of flight.

- Quickened trend vectors should be left out. This will reduce the amount of symbols, which reduces the likelyhood that the display becomes cluttered.
- Only the PFPA should be quickened, and this symbol should be used for throttle control.

Removing the quickened acceleration and vertical speed, forces the subject to mentally construct a line between the target acceleration and target vertical speed. The crossing of this line with the centerline of the pitch ladder is the set-point for the PFPA. For the subjects this is a difficult task to perform in the display, which had bugs on the trend vector tapes. It is expected that this problem will be less in the new display format.

- It has to be verified whether the new display format provides a more clear indication of the distribution vector and the energy error indications.
- The presentation of the required location of the PFPA symbol might be a solution to get better open loop thrust control in case of a command change.

The expected disadvantage is close loop control of the thrust in case of small deviations. This results in more control action, which is undesired.

- One might consider to only present a symbol indicating the required PFPA if big throttle actions should occur.

The display has been decluttered. It now has to be verified if addition of other information, which is normally presented on a PFD, does not conflict with the current display format. Therefore, the following changes or additions need to be made to the display format:

- Scale markers such as Vstall, Vstall warning, V1, VR, V2, flap limit speeds, radio altimeter information for low altitude awareness need to be added.
- Pitch limit indicators, unusual attitude recovery symbology, flight director, glideslope and localizer indicators need to be added.
- The artificial horizon should always stay visible, so for high pitch maneuvers at least a few degrees of the brown earth has to stay visible for attitude awareness.

Other suggestions and comments:

- The crew will have to get acquainted with the strategy and format of the EMPFD. In connection with the cost needed for the training of the crew, it is required to know how much effort it will take to retrain the crew.
- The Side Vertical Situation Display (SVSD) can possibly also be scaled in terms of energy. This requires further consideration.
- In the DELPHINS II simulator, an extension to the

Total Heading Control System (THCS) has already been made. Roll and turn rate are displayed.

- The aircraft model should be expanded with a wings leveller to prevent the heading from running slowly away.
- Several EMPFD concepts could be integrated with perspective flight path displays. This needs to be further addressed.

APPENDIX A: AIRCRAFT MODEL DESIGN

The aircraft model can be generated from classical flight dynamics and standard inertial equations. For this purpose, principles and equations found in reference 24 were used. Only the longitudinal movements of the aircraft will be used during the experiments. With respect to the required detailed information on energy related parameters, a point-mass model will provide enough information and will keep the level of detail manageable. For a point-mass model the forces working on the aircraft will cause a movement of the centre of gravity which is the velocity vector of the aircraft. The origin is the centre of gravity and the co-ordinate system is earth referenced with the X-axis defined positive in the direction of flight and the Z-axis defined positive to the centre of the earth.

The equation of motion can now be generated from Newton's second law

$$\sum F = m a = m \frac{dv}{dt}, \tag{A.1}$$

where m is mass, a is acceleration, v is speed and t is time. The forces F can be calculated from standard aerodynamics approximation equations. In the aerodynamics the Rayleigh equation is used to get undimensional force coefficients C_L and C_D for lift L and drag D

$$L = C_L \cdot \tfrac{1}{2} \rho V^2 S \tag{A.2}$$

and

$$D = C_D \cdot \tfrac{1}{2} \rho V^2 S\,. \tag{A.3}$$

Here ρ is the density, V is the airspeed and S is the wing area. For wings with an aspect ratio of $A>\approx 4$, an assumption can be made for the lift coefficient which is based on an elliptical distribution of the lift

$$C_L = C_{L_0} + \frac{2\pi}{1 + \frac{2}{A}} \cdot \alpha\,, \tag{A.4}$$

where C_{L0} is the lift coefficient for an angle-of-attack α of zero. The lift coefficient C_L is used to calculate the induced drag coefficient. The total drag coefficient is composed of the parasite drag coefficient $C_{D,0}$ and the induced drag coefficient. The resulting total drag coefficient C_D is called the drag polar

$$C_D = C_{D,0} + \frac{C_L^2}{\pi A e}\,, \tag{A.5}$$

where e is the Oswald factor (roughly between 0.7 and 0.9). Thrust is calculated by the engine model and weight is set as a constant parameter in the simulation.

The horizontal and vertical component for the equation of motion can now be calculated. Figure 1 shows the direction of the forces.

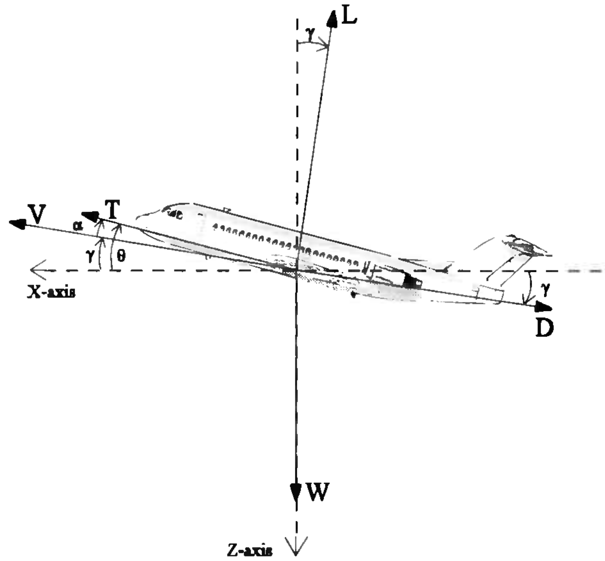

Fig. A.1. Forces working on aircraft

$$\sum F_x = T \cdot \cos\theta - L \cdot \sin\gamma - D \cdot \cos\gamma \tag{A.6}$$

and

$$\sum F_z = T \cdot \sin\theta + L \cdot \cos\gamma - D \cdot \sin\gamma - W \tag{A.7}$$

where θ is the pitch attitude, α is the angle-of-attack and γ is the flight path angle.

From the equation of motion the vertical speed v_z and horizontal speed v_x is calculated. The true airspeed is calculated from the compound vectors

$$V = \sqrt{v_x^2 + v_z^2}\,. \tag{A.8}$$

The flight path angle is the angle between the horizon and speed vector and can be calculated with

$$\gamma = \operatorname{atan} \tfrac{v_z}{v_x}\,. \tag{A.9}$$

The true airspeed and the flight path angle are used as feedback parameters. True airspeed is necessary for calculation of the aerodynamic forces (equations A.2 and A.3) and from the flight path angle, the angle-of-attack is calculated by

$$\alpha = \theta - \gamma\,. \tag{A.10}$$

Here θ is the pitch attitude. Normally pitch attitude is calculated with stability equations. The result will be a non-stabilised aircraft, meaning the pilot in control has the duty to stabilise it. The model also gets quite complicated by using the stability equations. Because the main item here is the evaluation of the display, the model must not be too difficult to handle. Pilots flying the model must be able to control it easily in a short training time. Otherwise, too much time will be spent on training to get acquainted with the model characteristics.

For the experiment a force-feedback stick is available. In handling qualities this will not be comparable with a column wheel or a flight stick, but it will be comparable to a side-stick. A side-stick is often accompanied by an augmentation system for stabilisation. So, the choice was made to automatically stabilise the aircraft model and make it a pitch rate command attitude hold system. Therefore, the model was not first developed as a unstabilised aircraft with augmentation added to it, but the aircraft was developed as an aircraft with neutral stability characteristics. For the calculation of the pitch rate command elementary dynamic characteristics are used from research by McRuer [ref. 18]. The transfer function from stick input δ_{stick} to pitch θ is given by

$$\theta = \frac{1}{s} \cdot \frac{1}{\tau_{elev} s + 1} \cdot \delta_{stick} \,. \tag{A.11}$$

Here τ_{elev} is the time constant for elevator control.

To prevent pilots from stalling the aircraft, a stall prevention is modelled. If the angle-of-attack crosses a predefined stall prevention angle, pitch is decreased until the angle-of-attack is less than the stall prevention angle. The model has no stall characteristics, so it should never be used for experiments with slow speed and high angle-of-attack.

APPENDIX B: ENGINE MODEL DESIGN

Engines are very complex machines to model mathematically. A lot of parameters are involved and they behave very nonlinear. The DELPHINS II simulator needed a simple model with a small amount of parameters for adjustment.

The main factors affecting thrust [ref. 24, pp. 152-178] are atmosphere and velocity. Corrections have to be made when the atmosphere conditions deviate from the standard conditions. The ideal thrust is defined as

$$T_{id} = (\dot{m}_a + \dot{m}_f) v_e - \dot{m}_a V \tag{B.1}$$

where $\dot{m}_a$ is the air mass flow, $\dot{m}_f$ is the fuel mass flow, v_e is the average exhaust gas speed, V is the true airspeed. The fuel mass flow is only a few percentages of the total mass flow. If fuel mass flow is neglected thrust is approximated by

$$T_{id} \approx \dot{m}_a (v_e - V) \tag{B.2}$$

If height is increased, pressure and temperature of the atmosphere change, which means a change of the mass flow through the engine. The mass of the air flow is directly proportional to the outside air pressure p and inversely proportional to the temperature Γ. This means, the atmosphere effect on the mass flow is

$$\frac{\dot{m}_a}{\dot{m}_{a\,sl}} = \frac{p}{p_{sl}} \cdot \frac{\Gamma_{sl}}{\Gamma} \,, \tag{B.3}$$

where sl means the condition of the parameter at sea level. Combining equation B.2 and equation B.3 the effect on the thrust will be

$$\eta_{atmosphere} = \frac{p}{p_{sl}} \cdot \frac{T_{sl}}{T} \tag{B.4}$$

From the thrust equation B.1 may be concluded that thrust decreases when airspeed increases. This is called the ram drag. But this is not the only influence of the airspeed. There is also a ram recovery obtained from the onflowing air. Ram recovery is the regaining of thrust as the kinetic energy of the onflowing air flow is converted to pressure in the inlet. The pressure at the compressor inlet then also grows, which again results in an increase in the compressor-end-pressure. The expansion in the turbine gains and because of this the gas exhaust speed increases, which means also increase of thrust. The ram drag is roughly approximated to be inversely proportional with the Mach number and the ram recovery is roughly approximated to be squared proportional with the Mach number. These approximations will only be applicable for Mach numbers below Mach 1.0.

Now M_{ref} is defined as the Mach number where the thrust is equal to the thrust at a Mach number of zero. The effect of the Mach number can then be calculated by

$$\eta_{Mach} = 1 - \frac{M}{M_e} + \left(\frac{M}{M_{ref}} \right)^2 \tag{B.5}$$

Here M is the actual Mach number of the aircraft engine combination and M_e is the exhaust Mach number, which is engine dependent. From simulation of the unmixed flow turbofan and mixed flow turbofan engine, with the gas turbine simulator program "GASTURB 6.0" [ref. 25], exhaust Mach numbers M_e and reference Mach numbers M_{ref} of these engines were obtained at several bypass numbers. The reference Mach number appeared to be roughly the same for all of the engine types, namely:

$$M_{ref} = 1.62 \,. \tag{B.6}$$

The exhaust Mach number results were fitted by a function showed by figure B.1. The overall function for the exhaust Mach number will then be:

$$M_e = 0.7 + p_1 \cdot \exp(p_2 \cdot bypass) \,, \tag{B.7}$$

where p_1 is 1.2 for the unmixed turbofan and 1.7 for the mixed turbofan and p_2 is 0.65 and 0.3 respectively. From figure B.1 also can be seen that a mixed flow turbofan should not be simulated with a bypass higher than 1.5.

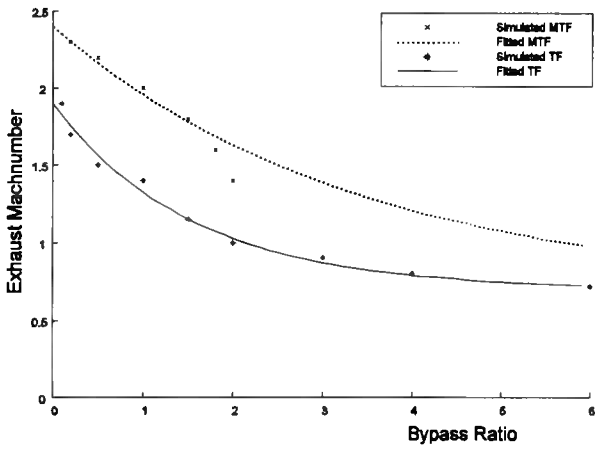

Fig. B.1. Fitting function of exhaust Mach number M_e for different bypass numbers of the Turbofan Engine (TF) and Mixed Flow Turbofan Engine (MTF).

In reference 19 paragraph 8.5.1 the transient performance of the engine is modelled by a simple exponential relaxation function with a dependent time constant. This can be modelled with a first order transfer function. From simulation with GASTURB [ref. 25] was concluded that a better transfer function will be a second order transfer function with roughly the same time constant τ and a small percentage overshoot *po* from the current step change. The transfer function will be:

$$G(s)_{\text{thrust}} = \frac{\omega_n^2}{s^2 + \zeta\omega_n s + \omega_n} \quad \text{(B.8)}$$

with

$$\zeta(\text{po}) = \begin{cases} \sqrt{\left(\frac{\ln\left(\frac{po}{100}\right)}{\pi}\right)^2 \Big/ 1 + \left(\frac{\ln\left(\frac{po}{100}\right)}{\pi}\right)^2}, & \text{for po} > 0 \\ 1, & \text{for po} = 0 \end{cases} \quad \text{(B.9)}$$

and

$$\omega_n(\zeta, \tau) = \frac{2.16 \cdot \zeta + 0.6}{\tau} \quad . \quad \text{(B.10)}$$

The throttle is designed to have an almost linear slope from idle thrust T_{idle} to max thrust T_{max}. Now the nett reference thrust $T_{net,ref}$ will be defined as the nett thrust at sea level with Mach number zero:

$$T_{\text{net,ref}} = T_{\text{idle}} + (T_{\max} - T_{\text{idle}}) \cdot \delta_{\text{throttle}}, \quad \text{(B.11)}$$

where $\delta_{throttle}$ is the throttle position

Now the actual thrust can be calculated from the merged equations B.11, B.4, B.5 and B.8.

$$T_{\text{net}} = T_{\text{net,ref}} \cdot \eta_{\text{atmosphere}} \cdot \eta_{\text{Mach}} \cdot G(s)_{\text{thrust}} \quad \text{(B.12)}$$

APPENDIX C: MODE ANNUNCIATOR PANEL

For check out and performance evaluation, tasks were needed. In an aircraft with autopilot the current task commands are displayed on the Mode Annunciator Panel (MAP). So a self designed MAP was appended to the display to show the pilot his current command mode, his next command mode and his next command (see fig. C.2).

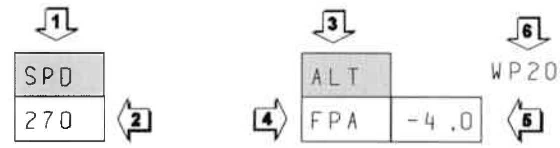

Fig. C.1. Mode Annunciator Panel

1. *Current speed mode (green)*
2. *Next speed command (green)*
3. *Current vertical navigation mode*
4. *Next vertical navigation mode*
5. *Next vertical navigation command*
6. *Next waypoint indicator (green)*

For this experiment the tasks given are combined FPA and speed commands or combined altitude and speed commands. The next command mode (#4) and commands (#2 and #5) will illuminate five seconds before this command will be engaged. This next command annunciation will start blinking two seconds before engagement. At command change the current mode annunciators (#1 and #3) will change to their new mode and the waypoint indicator (#6) will change to the name of the next waypoint.

APPENDIX D: GAMMA DISPLAY QUICKENING

The following derivation refers to D. Bray's work.

Consider

$$L = C_l \cdot \frac{1}{2} \cdot \rho \cdot V^2, \quad \text{(D.1)}$$

then

$$\Delta L = C_{l_\alpha} \cdot \Delta\alpha \frac{1}{2}\rho V^2 + C_{l_0} \cdot \frac{2}{V}\frac{1}{2}\rho V^2 \cdot \Delta V = = \text{W} \cdot \left(\frac{C_{l_\alpha}}{C_{l_0}} \cdot \Delta\alpha + 2 \cdot \frac{\Delta V}{V} \right) \quad \text{(D.2)}$$

For level flight at constant lift the relationship between alpha and speed is therefore

$$\frac{\Delta\alpha}{\Delta V} = \frac{2 \cdot C_{l_0}}{V \cdot C_{l_\alpha}} \quad \text{(D.3)}$$

For an approximate short period response the speed change may be neglected. Then

$$n_z = \frac{\Delta L}{W} = \frac{C_{l_\alpha}}{C_{l_0}} \cdot \Delta\alpha\ , \qquad (D.4)$$

or

$$\ddot{h} = V \cdot \dot{\gamma} = g \cdot \frac{C_{l_\alpha}}{C_{l_0}} \cdot (\theta - \gamma), \qquad (D.5)$$

or

$$\gamma\left(1 + \tau_\gamma s\right) = \theta \qquad (D.6)$$

where

$$\tau_\gamma = \frac{V}{g}\frac{C_{l_0}}{C_{l_\alpha}}, \qquad (D.7)$$

so that

$$\frac{\gamma}{\theta} = \frac{1}{1 + \tau_\gamma s} \qquad (D.8)$$

Thus we see that gamma lags pitch by τ_γ .This we also find when comparing the general form transfer functions of

$$\frac{\theta}{\delta_e} = K_{\theta/\delta_e} \cdot \frac{\left(1+\tau_{\theta_2} s\right)\left(1+\tau_{\theta_1} s\right)}{\left(s^2 + 2\zeta\omega_{sp} s + \omega_{sp}^2\right)\left(s^2 + 2\zeta\omega_{ph} s + \omega_{ph}^2\right)} \qquad (D.9)$$

and

$$\frac{\gamma}{\delta_e} = K_{\gamma/\delta_e} \cdot \frac{\left(1+\tau_{\theta_1} s\right)}{\left(s^2 + 2\zeta\omega_{sp} s + \omega_{sp}^2\right)\left(s^2 + 2\zeta\omega_{ph} s + \omega_{ph}^2\right)} \qquad (D.10)$$

Of course $\tau_{\theta_2} = \tau_\gamma$. The implication is that we can quicken a gamma display, so that in the transient response it will look like pitch and during tracking with the controls at neutral the gamma display will indicate true gamma:

$$\gamma_{\substack{quickened \\ for\ display}} = \gamma + \frac{\tau_\gamma s}{1 + \tau_\gamma s} \cdot \theta \qquad (D.11)$$

APPENDIX E: PILOTING TASKS

Combined flight path angle command and speed command task is presented by figure E.1 and E.2.

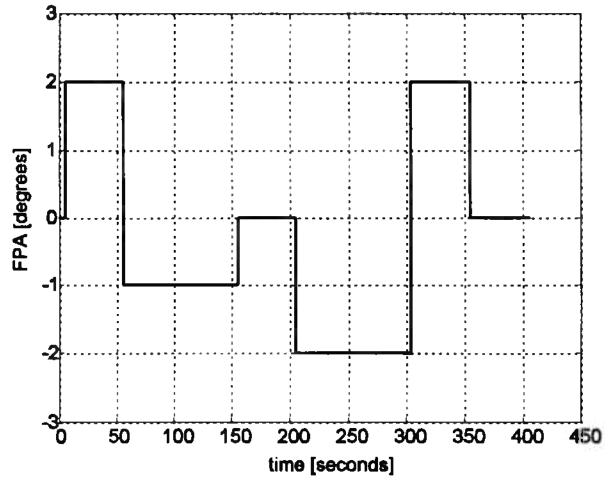

Fig. E.1. FPA task

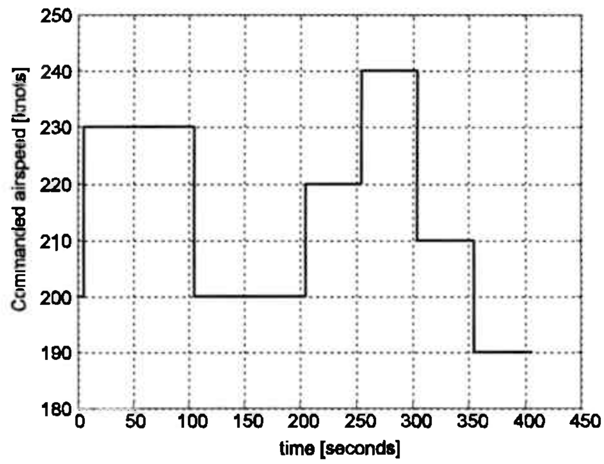

Fig. E.2. Speed command for FPA task

Combined altitude command and speed command task is presented by figure E.3 and E.4.

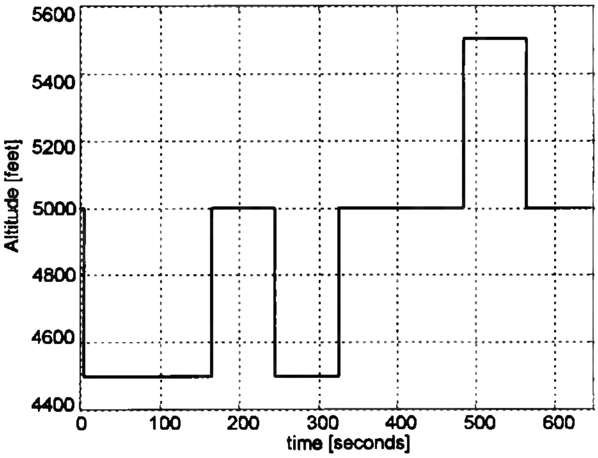

Fig. E.3. Altitude task

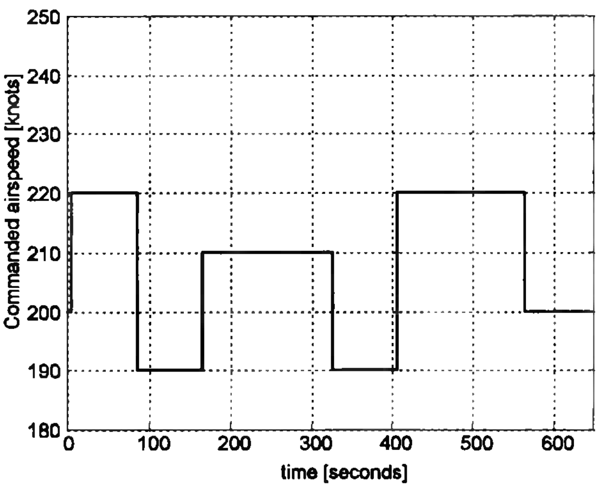

Fig. E.4. Speed command for altitude task

ABBREVIATIONS AND SYMBOLS

Abbreviations

ADC	Air Data Computer
ADI	Attitude Direction Indicator
AFCS	Automatic Flight Control Systems
ATC	Air Traffic Control
ATM	AirTraffic Management
DELPHINS	Delft Program for Hybridized Instrumentation and Navigation Systems
EFIS	Electronic Flight Instrument System
EMFCD	Energy Management Flight Control Display
EMPFD	Energy Management Primary Flight Display
FAA	Federal Aviation Administration
FCD	Flight Control Display
FCS	Flight Control System
FPA	Flight path angle
HGS	Head-Up Guidance System
HUD	Head-Up Display
IAS	Indicated Airspeed
MAP	Mode Annunciator Panel
MECS	Modified Energy Control System
MIMO	Multi-input / multi-output
MTF	Mixed Flow Turbofan
PFD	Primary Flight Display
PFPA	Potential flight path angle
SISO	Single-input / single-output
SVSD	Side Vertical Situation Display
TECS	Total Energy Control System
TF	Turbofan
THCS	Total Heading Control System

Symbols

a	acceleration
A	aspect ratio
B	bypass
C_D	drag coefficient
$C_{D,0}$	parasite drag coefficient
C_L	lift coefficient
D	drag
e	Oswald factor
$\dot{E}_{S_N}$	non-dimensional specific total energy rate
F	force
g	acceleration of gravity
$G(s)$	transfer function
h	altitude
$\dot{h}$	vertical speed
L	lift
m	mass
$\dot{m}_a$	air mass flow
$\dot{m}_f$	fuel mass flow
M	Mach number
M_e	exhaust Mach number
M_{ref}	reference Mach number
p	pressure
po	percentage overshoot
S	wing area
T	thrust
$T_{net,ref}$	nett reference thrust at sea level
v_e	exhaust gas speed
V	true airspeed
$\dot{V}$	acceleration
W	weight
α	angle-of-attack
γ	flight path angle (FPA)
γ_p	potential flight path angle (PFPA)
Γ	temperature
δ_{stick}	stick deviation
$\delta_{throttle}$	throttle position
ζ	damping ratio
η	relative effect

θ	pitch attitude
τ	time constant
τ_γ	time constant for quickened FPA
$\tau_{\gamma p}$	time constant for filtering of PFPA
τ_{elev}	time constant for elevator control
ω_n	radial frequency

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Briefing guide and questionnaire for the

Energy Management Primary Flight Display Experiment

May 1999

PREFACE

This document contains the Briefing Guide for the Energy Management Primary Flight Display experiment, which will be held in May 1999. The Briefing Guide gives a concise description of the piloted experimental set up.

After the introduction to the experiment objectives, the experimental set up will be discussed. This will be followed by the display layout and pilot strategies. Furthermore the pilot questionnaire can be found in this document.

Table of Contents

1. Introduction and background

1.1. Background on TECS

The Total Energy Control System (TECS) is an automatic flight control system for longitudinal flight path and speed control. It uses a single generalized multi input / multi output control algorithm to provide complete operational and performance consistency for all modes and flight conditions. The TECS design uses thrust to control total energy and the elevator to control energy distribution, to satisfy flight path and speed targets. The result is a pilot-like, energy efficient operation that solves the age-old control coordination and energy management problems of current generation of autopilots and autothrottles.

The TECS concept was developed largely under NASA funding and was first flight demonstrated on the NASA B737 aircraft. Also, extensive pilot in the loop evaluation were conducted for the B737 and B747 flight simulators. Subsequently TECS was applied and flown on the Condor High Altitude Long Endurance aircraft technology demonstration program. Although these programs have been highly successful, the TECS design has not yet been introduced in production aircraft.

1.2. Introduction

The TECS multi-input / multi-output control law makes it possible to achieve decoupled command responses. As a result, a change in flight path angle command will not cause a significant speed deviation and vice versa. Another way to look at command response decoupling is to realize that for a flight path angle or an acceleration command change, the additional energy added/removed by the throttle has to be distributed fully into/from potential or kinetic energy depending on the command, otherwise energy is added to or subtracted from the variable that is commanded to be held constant. This task needs precise thrust and elevator control coordination which are related to each other.

The TECS display shows all of the information needed by the pilot to control and distribute the energy of the aircraft. Now the pilot is able to coordinate thrust and elevator control to achieve decoupled command responses. The TECS display also allows the pilot to supervise the TECS control system in case of automated flight.

The purpose of the experiment is to investigate the advantages/disadvantages for pilot handling and acceptance. Pilot comments as well as performance measures will be used to get a first impression and to identify potential problem areas with respect to pilot handling and acceptance.

2. Experiment information

2.1. Experiment objectives

The general research objectives are:

1. To collect pilot subjective acceptance and performance data.
2. To evaluate the pilot's awareness of the aircraft's energy state and the possibilities with it.
3. To evaluate the pilot's ability to cope with a non standard Primary Flight Display (PFD) with a moving and scaling speed and altitude tapes.

2.2. Mission description

General statements of the required operations are:

1) **What is pilot-vehicle combination required to accomplish?**

Manually follow the flight path angle and speed commands or altitude and speed commands. Priority must be given to the vertical tracking task, but speed should not be used to get better performance on the vertical tracking task. In other words, speed may never go in the opposite direction of the speed target, due to a change in the vertical path. For this reason acceleration should always be in the direction of the speed target.

2) **What are the conditions under which these required operations are to be carried out?**

Normal aircraft state, clean configuration, initial speed will be set by pilot in initial condition according to commanded initial speed, aircraft mass 20.000 kg, no wind, no turbulence. The aircraft lateral movements are disengaged.

3) **What are the provisions for familiarization and are additional runs allowed?**

Performance will be measured during the training flights. When performance reaches a sufficient level and stabilizes, training flights will end. If the pilot indicates that performance can still improve on a short time base, more training flights will be issued.

2.3. Aircraft / Simulator description

Test vehicle:

The TU Delft's Delphins II fixed-base part task research flight simulator with three advanced side by side LCD display panels. The left panel is used for displaying the engine instruments and the middle panel for the PFD and mode annunciator panel. The right display panel is not used for this experiment.

Simulated aircraft:

Fokker F-28 with a constant mass of 20.000 kg. The F-28 is equipped with 2 Rolls-Royce "Spey" 555-15 TurboFan engines with 43.8 kN of thrust each.

Cockpit interface:

- Force-feedback stick with stick-force proportional to stick deflection. The stick is only operating in the longitudinal direction.
- Throttle box with two throttle levers for twin engine control.

Cues provided:

- Engine instruments become yellow if caution line motor limits are crossed. They become red if warning line motor limits are crossed.
- There are no motion cues provided.
- There is no external vision provided.

2.4. Measured parameters for concept rating

Pilot-vehicle output:	Flight mechanical parameters, control variables
Pilot control effort input:	Stick and Throttle

2.5. Pilot Evaluation Data

Pilots will fly all three different display configurations. Afterwards they will be asked to evaluate and comment on several aspects of the experiment, for instance the usefulness of the energy management symbols. Additionally, objective data will be collected through measurement of aircraft performance variables.

2.6. Experiments

Pilots will participate for one full day from 8:30 AM until 17:00 PM.
In the morning there will be familiarisation and training flights. In the afternoon the experiments will take place.

2.7. Anonymity

All results of the experiment will be treated with discretion. No personal or company names will be related to any of the outcomes of the experiment

3. Experimental layout

3.1. Piloting task

The experiment is focussed on manual flight operations. The pilot is asked to execute combined flight path angle and speed commands or altitude and speed commands tasks. Commands are all displayed on the PFD by green bugs. There is a target speed bug on the speed tape, a green target altitude bug on the altitude tape and a green target fpa symbol on the Attitude Indicator (AI). Altitude and fpa commands will never be given simultaneously.

On the Mode Annunciator Panel (MAP) the next commands will illuminate five seconds before this command will be engaged. This next command annunciation will start blinking two seconds before engagement. On engagement of the new commands target bugs will move to their new position. Action for new commands should <u>not</u> occur before commands are changed. The command preview is provided to get your attention for the next command. It can be used for anticipation on what your next actions will be, but do <u>not</u> act before the change of commands.

The actual profile of the commanded task will not be given in advance. Similar profiles will be flown in the training phase, so the pilot can familiarize with the system and the behaviour of it.

3.2. Display layouts

In this experiment three different display configurations will be used. The first display configuration is the basic configuration. It is a standard PFD with a fpa symbol. There is an acceleration bug (#7) displayed right of the speed tape and its first scale marker marks 2 knots/s. There is a vertical speed bug (#5) displayed left of the altitude tape and its first scale marker marks 3000 ft/min. So the derivatives of the tapes will be displayed on the inside of the display.

Display configuration 2 provides an extra symbol for the energy management task. It is the potential flightpath vector symbol . This carrot symbol (#4) displays the flightpath which can be flown with current airspeed and current power state of the aircraft. The speed and altitude will move up and down together with the horizon and the altitude tape will scale depending on the actual speed. The scaling of the altitude tape results in tapes that have an equal energy over length ratio. This means that 1 cm of speed increase on the speed tape will correspond with 1 cm of altitude increase on the altitude tape. The moving of both tapes with the horizon is necessary to couple the acceleration bug (#7) and the vertical speed bug (#5) to the carrot symbol(#4). They will now always be on a straight line which rotates round the carrot symbol by input of the elevator. The actual speed (#10) is opposite to the zero acceleration position and the actual altitude (#12) is opposite to the zero vertical speed position.

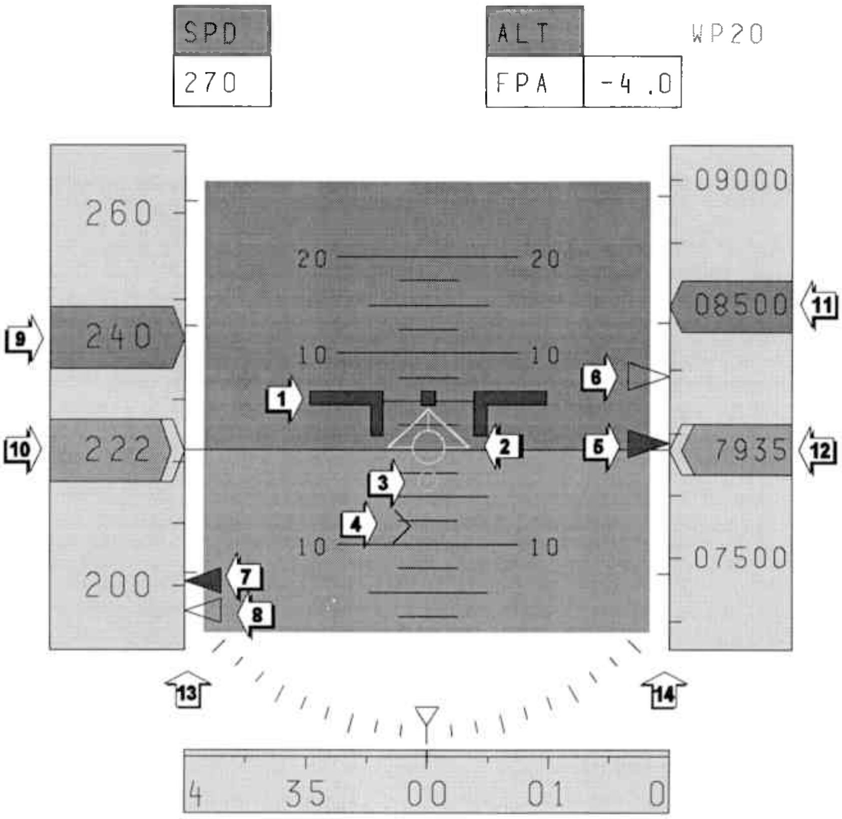


Figure 1: Display configuration 3

The list below gives an explanation for the symbols with corresponding numbers in figure 1.

1. *Aircraft attitude reference symbol*
2. *fpa with quickening*
3. *target fpa*
4. *quickened potential fpa (carrot symbol)*
5. *actual vertical speed bug*
6. *quickened vertical speed*
7. *actual acceleration bug*
8. *quickened acceleration*
9. *target speed*
10. *actual speed*
11. *target altitude*
12. *actual altitude*
13. *acceleration tape*
14. *vertical speed tape*

Display configuration 3 is presented in figure 1. It provides three more extra symbols for quickening of the symbols already displayed in display configuration 2. There is an open acceleration bug (#8) and an open vertical speed bug (#6). These are the quickened versions of the solid bugs (#5 & #7). The open acceleration bug (#8) is also quickened for thrust. This means a preview of the acceleration according to throttle setting is displayed. The third quickening symbol is the fpa (#2). An arrow will grow out of the fpa symbol to point to the quickened fpa position. This will only be the case if a lot of elevator input is used.

3.3. Control strategies

There are five possible command changes. For every situation a strategy is provided. The strategy is the same for all display types, but in some of the displays energy management information is missing. Here the pilot has to make an estimation of the energy management parameters.

1) **change in fpa with constant speed**
- check if power has to be added or reduced and adjust throttle likewise
  - if the carrot symbol is displayed, set it on the new fpa target
- use the elevator to move to the target fpa
  - keep the acceleration opposite to the target speed indicator
- tune throttle for the target fpa and target speed

2) **change in altitude with constant speed**
- check if power has to be added or reduced and adjust throttle likewise
  - if the carrot symbol is displayed, set it between the two target indicators
- use the elevator to keep speed on target, while climbing to the target altitude
  - keep the vertical speed indicator opposite to the altitude target indicator
  - keep the acceleration indicator opposite to the speed target indicator
- adjust throttles and elevator to level off while keeping the speed on target
  - if the carrot symbol is displayed, keep it on the fpa symbol while using the elevator for setting the fpa symbol at the horizon

3) **speed change only**
- check if power has to be added or reduced and adjust throttle likewise
  - if displayed, move the carrot symbol to the fpa target (zero for constant altitude task) plus or minus the length of the speed target projected on the centre axis towards the reference point on the vertical speed tape (the acceleration indicator will be opposite to the speed target indicator then)
- use the elevator to stay on the fpa or altitude target
  - the vertical speed indicator can help keeping altitude constant
- tune throttle and elevator to capture the target speed while keeping the other target constant
  - keep the acceleration indicator opposite to the speed target
  - if displayed the carrot symbol should be set at the target fpa (zero for constant altitude task) to have no acceleration or deceleration

4) **combined fpa and speed change**

- check if power has to be added or reduced and adjust throttle likewise
  - if the carrot symbol is displayed, set it on the target fpa plus or minus the length of the speed target projected on the centre axis towards the reference point on the vertical speed tape
- use the elevator to set fpa on target fpa, while keeping speed going in the right direction or keep it constant, but don't let it diverge from the speed target
  - keep the acceleration indicator between the speed target and the actual speed
- proceed further as speed change

5) **combined altitude and speed change**
- check if power has to be added or reduced and adjust throttle likewise
  - if the carrot symbol is displayed, set it between the speed target indicator and altitude target indicator
- use the elevator to get into the right direction of the altitude target while keeping speed going in the right direction or keep it constant, but don't let it diverge from the speed target
  - keep the vertical speed indicator opposite to the altitude target
- use throttles and elevator to capture the altitude target. It is possible that the speed capture has to be performed simultaneously.
  - if displayed, keep the carrot symbol during the capture between the two target indicators
- if the altitude is on target before the target speed is obtained, proceed further as speed change

These strategies assume there is enough thrust to work with the symbols. If the engines don't provide enough thrust to carry out the task, be careful not to overspeed or overheat the engines. Try to carry out the task with less thrust.

Always keep in mind that total energy is controlled by the throttle and the energy is distributed by the elevator.

4. Pilots' questionnaire

Please fill out the questionnaire below after all three experiments.

4.1. Acceptance and quality of basics

Acceptance of aircraft model

1) Do you think the aircraft model is realistic enough for this experiment?

☐ Yes
☐ No

2) Did you have problems in controlling the aircraft using elevator?

☐ Yes
☐ No

3) Did you have problems in controlling the aircraft using throttle?

☐ Yes
☐ No

Acceptance and quality of tapes of the EMPFD

1) What do you think of the moving references of the tapes?

☐ no problem at all
☐ confusing at first instance, but having no problem in adapting
☐ having problems to adapt to it
☐ impossible scales, must be improved
☐ unacceptable, fixed position needed

2) What do you think of the scaling of altitude tape?

☐ no problem at all
☐ confusing at first instance, but having no problem in adapting
☐ having problems to adapt to it
☐ impossible scale, must be improved
☐ unacceptable, fixed range needed

4.2. Questionnaire for standard PFD

Acceptance and quality of symbology

1) Did you ever fly with a thrust guidance system for manual control?

☐ Yes
☐ No

2) Having no thrust guidance information, did you miss it?

☐ Yes
☐ No
☐ No opinion

3) What do you think of the fpa indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

4) What do you think of the acceleration indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

5) What do you think of the vertical speed indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

Situational awareness

6) How easy was it to estimate and set the throttle position for the task?

☐ very hard
☐ hard
☐ moderate
☐ easy
☐ very easy

7) How often did you cross check the engine display?
☐ every second
☐ every 10 seconds
☐ every 30 seconds
☐ every minute
☐ seldom
☐ not at all

8) Did you have an overspeed or overheat of the engines?
☐ Yes
☐ No
☐ don't know

Perceived workload

Indicate on the scale below, your effort to control:

9) airspeed
1 2 3 4 5 6 7 8 9 10
→ increasing difficulty

10) fpa
1 2 3 4 5 6 7 8 9 10
→ increasing difficulty

11) altitude
1 2 3 4 5 6 7 8 9 10
→ increasing difficulty

4.3. Questionnaire for EMPFD

Acceptance and quality of symbology

1) Did you consciously make use of the fact that elevator rotates the acceleration indicator and the vertical speed indicator around the carrot symbol?

☐ very often
☐ sometimes
☐ never

2) Did you consciously make use of the fact that the distance on the speed and altitude tapes correspond to an equal amount of energy?

☐ very often
☐ sometimes
☐ never

3) What do you think of the fpa indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

4) What do you think of the acceleration indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

5) What do you think of the vertical speed indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

6) What do you think of the potential fpa (carrot) symbol?
- ☐ very helpful
- ☐ helpful
- ☐ neutral
- ☐ confusing, distracting
- ☐ interfering with other symbols: ....
- ☐ useless, did not use it

<u>Situational awareness</u>

7) How easy was it to estimate and set the throttle position for the task?
- ☐ very hard
- ☐ hard
- ☐ moderate
- ☐ easy
- ☐ very easy

8) How often did you cross check the engine display?
- ☐ every second
- ☐ every 10 seconds
- ☐ every 30 seconds
- ☐ every minute
- ☐ seldom
- ☐ not at all

9) Did you have an overspeed or overheat of the engines?
- ☐ Yes
- ☐ No
- ☐ don't know

<u>Perceived workload</u>

Indicate (vertical line) on the scale below, your effort to control:

10) airspeed 1 2 3 4 5 6 7 8 9 10

→ increasing difficulty

11) fpa 1 2 3 4 5 6 7 8 9 10

→ increasing difficulty

12) altitude 1 2 3 4 5 6 7 8 9 10

→ increasing difficulty

4.4. Questionnaire for EMPFD with quickening

Acceptance and quality of symbology

1) Did you consciously make use of the fact that elevator rotates the acceleration indicator and the vertical speed indicator around the carrot symbol?

☐ very often
☐ sometimes
☐ never

2) Did you consciously make use of the fact that the distance on the speed and altitude tapes correspond to an equal amount of energy?

☐ very often
☐ sometimes
☐ never

3) What do you think of the fpa indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

4) What do you think of the quickening of the fpa indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

5) What do you think of the acceleration indicator?

☐ very helpful
☐ helpful
☐ neutral
☐ confusing, distracting
☐ interfering with other symbols: ....
☐ useless, did not use it

6) What do you think of the quickened acceleration indicator?
- ☐ very helpful
- ☐ helpful
- ☐ neutral
- ☐ confusing, distracting
- ☐ interfering with other symbols: ....
- ☐ useless, did not use it

7) What do you think of the vertical speed indicator?
- ☐ very helpful
- ☐ helpful
- ☐ neutral
- ☐ confusing, distracting
- ☐ interfering with other symbols: ....
- ☐ useless, did not use it

8) What do you think of the quickened vertical speed indicator?
- ☐ very helpful
- ☐ helpful
- ☐ neutral
- ☐ confusing, distracting
- ☐ interfering with other symbols: ....
- ☐ useless, did not use it

9) What do you think of the quickened potential fpa?
- ☐ very helpful
- ☐ helpful
- ☐ neutral
- ☐ confusing, distracting
- ☐ interfering with other symbols: ....
- ☐ useless, did not use it

10) Do you think you also need a potential fpa symbol?
- ☐ Yes
- ☐ No
- ☐ No opinion

Situational awareness

11) How easy was it to estimate and set the throttle position for the task?

☐ very hard
☐ hard
☐ moderate
☐ easy
☐ very easy

12) How often did you cross check the engine display?

☐ every second
☐ every 10 seconds
☐ every 30 seconds
☐ every minute
☐ seldom
☐ not at all

13) Did you have an overspeed or overheat of the engines?

☐ Yes
☐ No
☐ No opinion

Perceived workload

Indicate (vertical line) on the scale below, your effort to control:

14) airspeed

1 2 3 4 5 6 7 8 9 10

→ increasing difficulty

15) fpa

1 2 3 4 5 6 7 8 9 10

→ increasing difficulty

16) altitude

1 2 3 4 5 6 7 8 9 10

→ increasing difficulty

Appendix G: Parameter initialization file


```
/* Initial conditions */
Vini            = 200               /* Initial true airspeed in knots */

/* Aircraft parameters */
CL0             = 0.13              /* Lift coefficient if alpha is zero */
CD0             = 0.05              /* Drag coefficient if lift coef. is zero */
Vmo             = 330               /* Maximum operating Equivalent Airspeed in knots */
Mmo             = 0.75              /* Maximum operating Mach number */
S               = 76.4              /* Wing area */
A               = 7.280522875817    /* aspect ratio wing */
e               = 0.8               /* Oswald factor for current wing */
m               = 20000             /* Total mass of airplane */

/* Engine parameters */
Engine          = 2                 /* 1 = Unmixed, 2 = Mixed Turbofan */
Bypass          = 1.0               /* Bypass ratio of engines */
Machref         = 1.62              /* Exaust speed where ram recovery is 1 */
tau_limu        = 2.5               /* Seconds it takes to spin up engine to 100% */
tau_limd        = 2                 /* Seconds it takes to spin down engine from 100% */
atmeff_flag     = 1                 /* Has the atmosphere effect on engine parameters? */
rameff_flag     = 1                 /* Has airspeed effect on engine parameters? */
                                    /* flags => 1=yes 0=no */
/* Handling parameters */
G_elev          = 0.08              /* Stick elevator gain */
G_stall         = 20                /* Stall prevention sensitivity */
G_ail           = 0.45              /* Stick aileron gain */
tau_theta       = 0.5               /* Time constant for elevator control */
tau_roll        = 0.4               /* Time constant for aileron control */
stall_angle     = 14                /* If alpha > stall_angle, pitch is decreased to prevent stall */
maxpitch        = 45                /* Maximum pitch angle in degrees */
minpitch        = -45               /* Minimum pitch angle in degrees */
maxroll         = 70                /* Maximum roll angle in degrees */
rollholdlim     = 30                /* Minimum roll angle limit during limiting in hold in degrees */

/* TECS Display parameters */
ptaugam1        = 45                /* multiplier parameter for tau_gamma (gamma quickening) */
ptaugam2        = -0.85             /* power parameter for tau_gamma (gamma quickening) */
ptpfpamin       = 0.1               /* minimum of tau_pfpfa (pfpa quickening) */
ptpfpamax       = 20                /* maximum of tau_pfpfa (pfpa quickening) */

/* Atmosphere parameters */          /* ICAO standard atmosphere */
g               = 9.80665           /* gravaty constant */
R               = 287.05287         /* gas constant */
psl             = 101325            /* pressure at sea level in kN */
Tsl             = 288.15            /* temperature at sea level in Kelvin */
dT              = 6.5e-3            /* decrement of atmosphere temperature per meter in Kelvin */
Ttrop           = 216.65            /* temperature at tropopause in Kelvin */
htrop           = 11000             /* height of tropopause in meters */
hgteff_flag     = 1                 /* Has height effect on airplane performance */
atm_hgt         = 10000             /* Initial atmosphere height (in ft) if hgteff_flag=0 */

/* Engine instruments */
/* Thrust */
comgamset       = 1                 /* Calculate req. thrust according to commanded gamma */
ThrustMin       = 0                 /* Minimum thrust at throttle idle setting */
```

```
ThrustMax     = 43800          /* Maximum thrust of one engine */
po_THR        = 0.0            /* Percentage overshoot of thrust */
tau_THR       = 2.5            /* Rise time of thrust is seconds */
/* Fuel Flow */
FFMin         = 737            /* Minimum Fuel Flow at idle position */
FFMax         = 2948           /* Maximum Fuel Flow at 100% throttle */
po_FF         = 12.0           /* Percentage overshoot of Fuel Flow */
tau_FF        = 1.0            /* Rise time of Fuel Flow in seconds */
FF_Mach_par   = 0.39           /* Influence parameter of Mach to Fuel Flow */
/* Low Pressure Spool Speed */
N1Min         = 0.27           /* Minimum LP spool speed at idle position */
N1Max         = 1.08           /* Maximum LP spool speed at 100% throttle */
po_N1         = 8.0            /* Percentage overshoot of LP spool speed */
tau_N1        = 3.0            /* Rise time of LP spool speed in seconds */
N1_Tamb_par   = 0.628323417    /* Influence parameter of ambient Temperature to LP spool speed */
N1_Mach_par   = -0.114618796   /* Influence parameter of Mach to LP spool speed */
N1rdlm6       = 108.5          /* N1 red line in Climb mode */
N1rdlm7       = 108.5          /* N1 red line in Cruise mode */
N1rdlm8       = 108.5          /* N1 red line in Go-Around mode */
N1rdlm9       = 108.5          /* N1 red line in Maximum Continuous mode */
N1dsmin       = 25             /* N1 minimum dynamic scale indication */
N1dsmax       = 120            /* N1 maximum dynamic scale indication */
/* High Pressure Spool Speed */
N2Min         = 0.48           /* Minimum HP spool speed at idle position */
N2Max         = 0.99           /* Maximum HP spool speed at 100% throttle */
po_N2         = 10.0           /* Percentage overshoot of HP spool speed */
tau_N2        = 3.0            /* Rise time of HP spool speed in seconds */
N2_Tamb_par   = 0.365980227    /* Influence parameter of ambient Temperature to HP spool speed */
N2_Mach_par   = -0.067620273   /* Influence parameter of Mach to HP spool speed */
N2rdlm6       = 98.5           /* N2 red line in Climb mode */
N2rdlm7       = 98.5           /* N2 red line in Cruise mode */
N2rdlm8       = 98.5           /* N2 red line in Go-Around mode */
N2rdlm9       = 98.5           /* N2 red line in Maximum Continuous mode */
N2dsmin       = 25             /* N2 minimum dynamic scale indication */
N2dsmax       = 110            /* N2 maximum dynamic scale indication */
/* Exaust Gas Temperature */
EGTMin        = 452            /* Minimum Exhaust Gas Temperature at idle position [K] */
EGTMax        = 773            /* Maximum Exhaust Gas Temperature at 100% throttle [K] */
po_EGT        = 25.0           /* Percentage overshoot of Exhaust Gas Temperature */
tau_EGT       = 4.0            /* Rise time of Exhaust Gas Temperature in seconds */
EGT_pamb_par  = 0.0731306086   /* Influence parameter of ambient Temp. to Exhaust Gas Temp. */
EGT_Mach_par  = 0.0228577167   /* Influence parameter of Mach to Exhaust Gas Temperature */
EGTcalm6      = 510            /* EGT caution line in Climb mode */
EGTcalm7      = 510            /* EGT caution line in Cruise mode */
EGTcalm8      = 510            /* EGT caution line in Go-Around mode */
EGTcalm9      = 510            /* EGT caution line in Maximum Continuous mode */
EGTrdlm6      = 520            /* EGT red line in Climb mode */
EGTrdlm7      = 520            /* EGT red line in Cruise mode */
EGTrdlm8      = 520            /* EGT red line in Go-Around mode */
EGTrdlm9      = 520            /* EGT red line in Maximum Continuous mode */
EGTdsmin      = 150            /* EGT minimum dynamic scale indication */
EGTdsmax      = 550            /* EGT maximum dynamic scale indication */

/* Simulation parameter */
timestep      = 0.0167         /* timestep of simulation */
```

Calculating Netto Thrust Ratio

Tsl = 288.15
psl = 101325
Machref = 1.62
if eng==1 Machexit=0.7+1.2*exp(-B*0.65); (Unmixed Flow Turbofan)
if eng==2 Machexit=0.7+1.7*exp(-B*0.3); (Mixed Flow Turbofan)

function nTr = nTr(eng,B,p,T,M)=1*(p/psl*Tsl/T)*(1-M/Machexit+(M/Machref)^2)

Calculating Rel. Corr.LP Spool Speed

Tsl = 288.15
pNLT=0.62832341679754
pNLM=-0.11461879606078

function NL = NL(T,M)=(Tsl./T).^pNLT + pNLM*M.^2

Calculating Rel. Corr. NH Spool Speed

Tsl = 288.15
pNHT=0.36598022712306
pNHM=-0.06762027261462

function NH = NH(T,M)=(Tsl./T).^pNHT + pNHM*M.^2

Calculating Rel. Fuel Flow

Tsl = 288.15
psl = 101325
Machexit = 1.9594
Machref = 1.6200
pFFM=0.0332

function FF = FF(p,T,M)=(1+M*pFFM)*(p/psl*Tsl/T)*(1-M/Machexit+(M/Machref)^2)

Calculating Exaust Gas Temperature

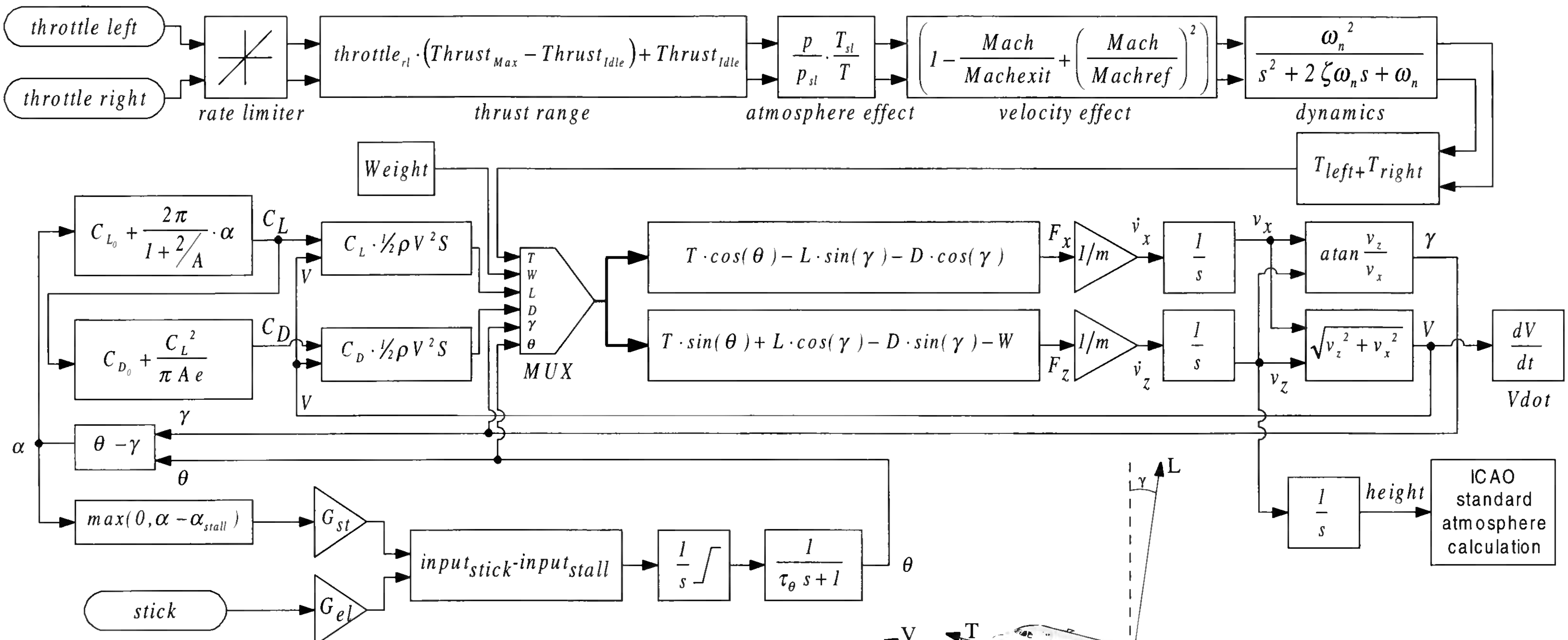
Tsl = 288.15
psl = 101325
pEGTM = 0.02285771671726
pEGTp = 0.07313060859644

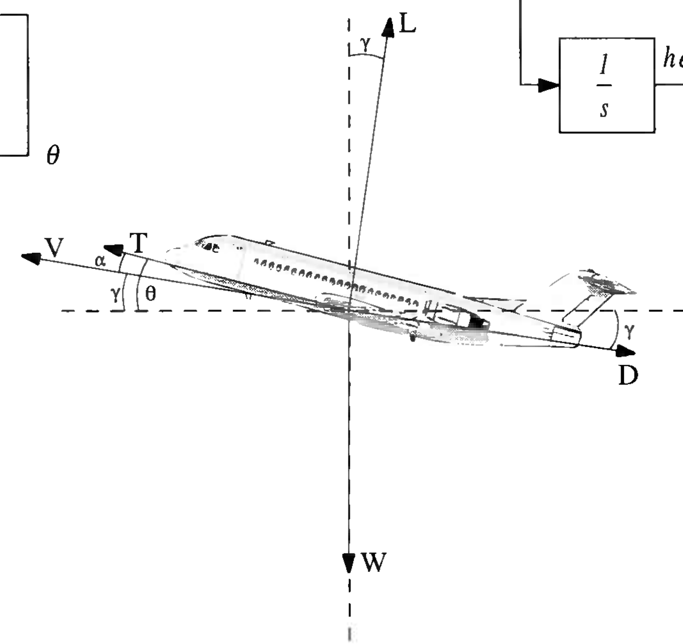
function EGT = EGT(p,T,M) =
=(740*((1-pEGTp)+pEGTp*(psl./p).^0.42)+(T-Tsl)).*(1+pEGTM*(M).^2)

Appendix I

Flightmodel drawings

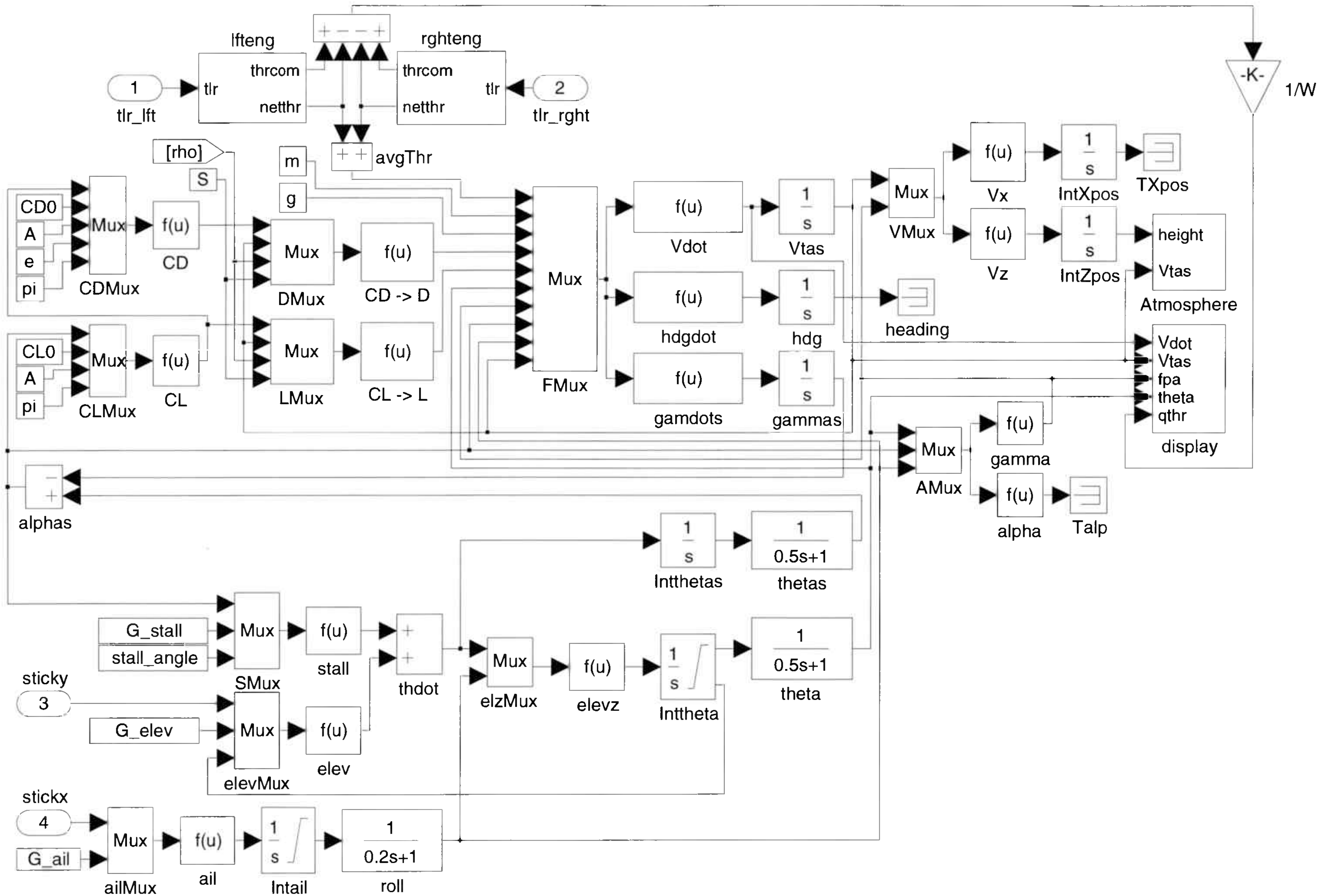
Flightmodel for the Energy Management PFD



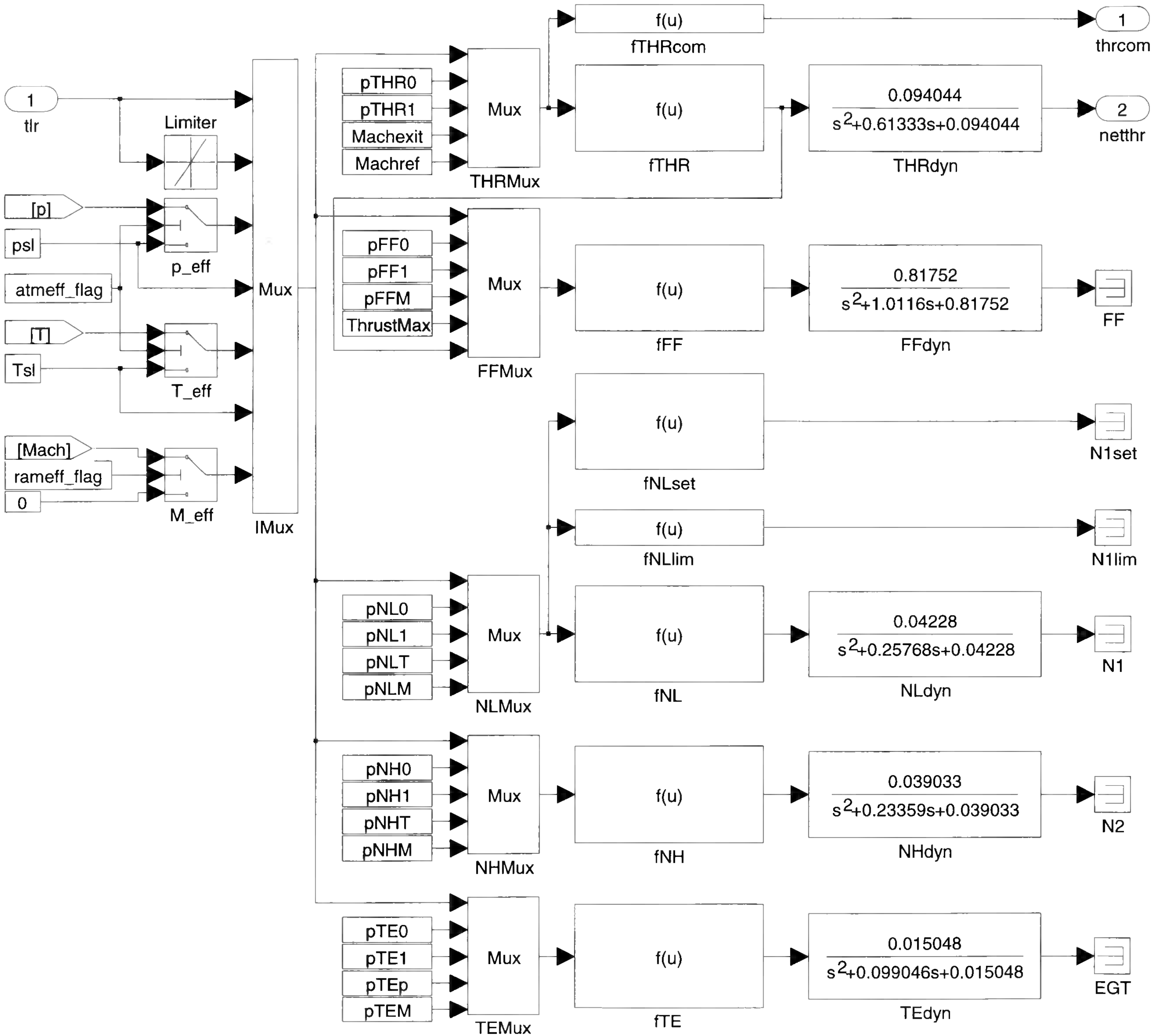


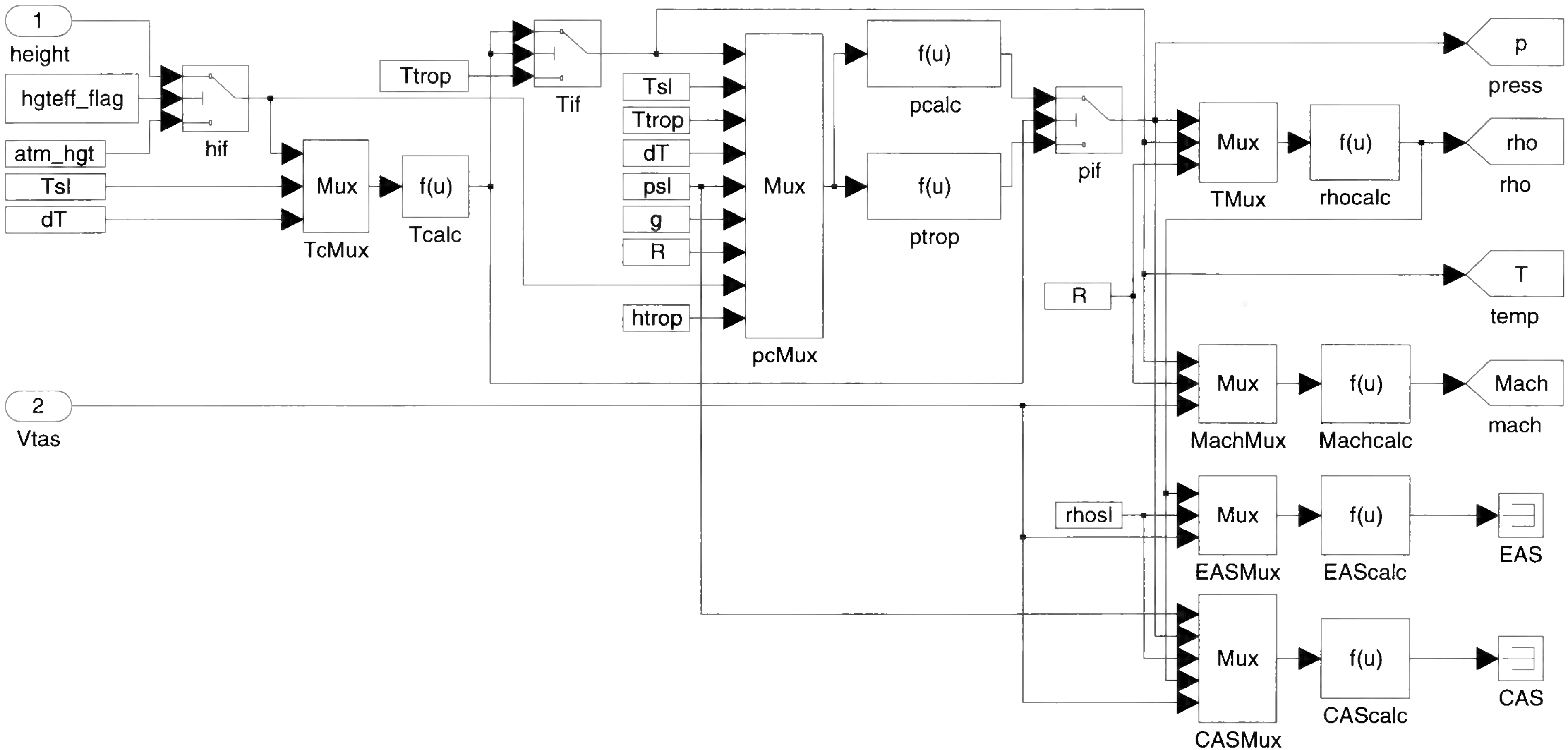
Machexit is Mach number of gas at engine nozzle
Unmixed Turbofan: Machexit=0.7+1.2·exp(-Bypass·0.65)
Mixed Turbofan: Machexit=0.7+1.7·exp(-Bypass·0.3)

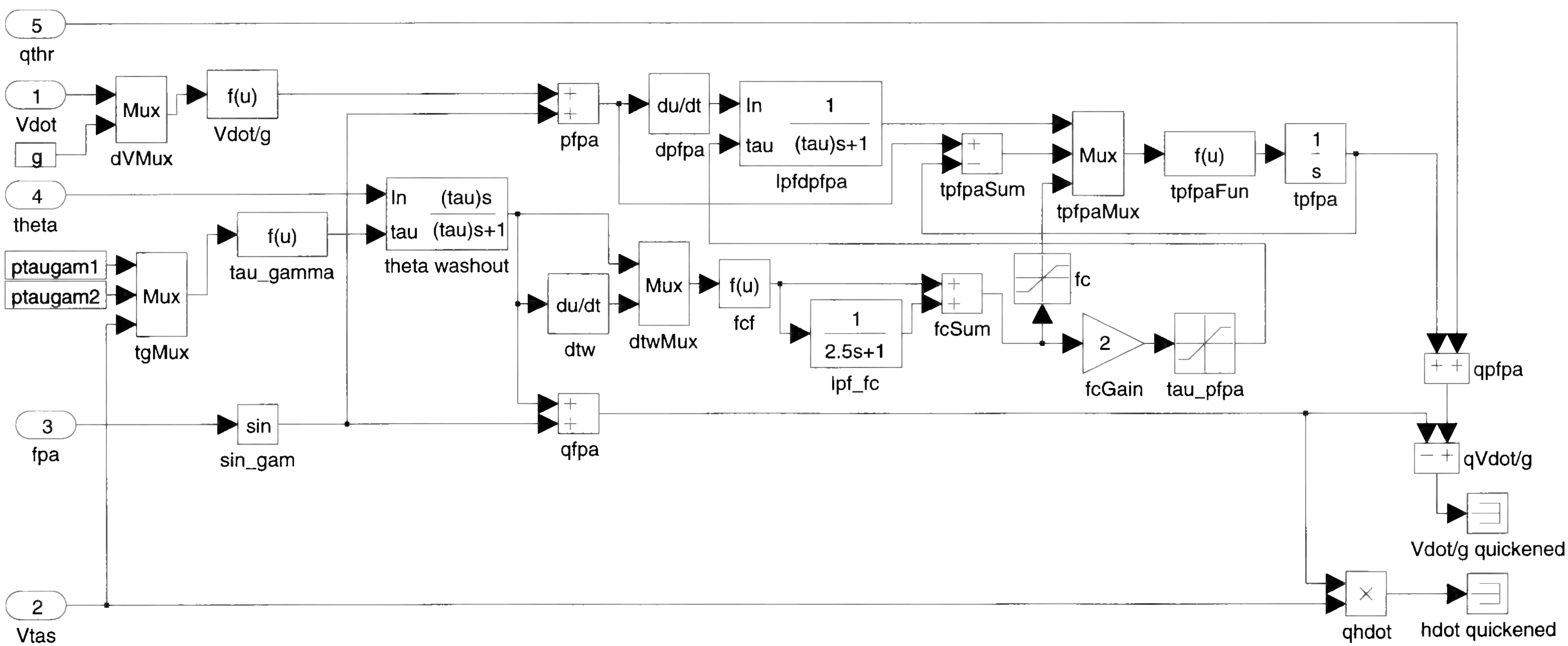
Machref is Mach number of engine where the Mach recovery is 100%
(Thrust at this Mach number is equal to thrust at Mach 0)
Machref = 1.62



lfteng
thrcom
tlr
netthr
rghteng
thrcom
tlr
netthr
1
tlr_lft
2
tlr_rght
-K-
1/W
[rho]
S
m
g
avgThr
CD0
A
e
pi
Mux
CDMux
f(u)
CD
Mux
DMux
f(u)
CD -> D
CL0
A
pi
Mux
CLMux
f(u)
CL
Mux
LMux
f(u)
CL -> L
Mux
FMux
f(u)
Vdot
1
s
Vtas
f(u)
hdgdot
1
s
hdg
f(u)
gamdots
1
s
gammas
Mux
VMux
f(u)
Vx
f(u)
Vz
1
s
IntXpos
1
s
IntZpos
TXpos
height
Vtas
Atmosphere
heading
Vdot
Vtas
fpa
theta
qthr
display
Mux
AMux
f(u)
gamma
f(u)
alpha
Talp
alphas
1
s
Intthetas
1
0.5s+1
thetas
Mux
SMux
G_stall
stall_angle
f(u)
stall
thdot
Mux
elzMux
f(u)
elevz
1
s
Inttheta
1
0.5s+1
theta
sticky
3
G_elev
Mux
elevMux
f(u)
elev
stickx
4
G_ail
Mux
ailMux
f(u)
ail
1
s
Intail
1
0.2s+1
roll


1
tlr
Limiter
[p]
psl
p_eff
atmeff_flag
[T]
Tsl
T_eff
[Mach]
rameff_flag
0
M_eff
Mux
IMux
pTHR0
pTHR1
Machexit
Machref
Mux
THRMux
f(u)
fTHRcom
f(u)
fTHR
0.094044
s2+0.61333s+0.094044
THRdyn
1
thrcom
2
netthr
pFF0
pFF1
pFFM
ThrustMax
Mux
FFMux
f(u)
fFF
0.81752
s2+1.0116s+0.81752
FFdyn
FF
f(u)
fNLset
N1set
f(u)
fNLlim
N1lim
pNL0
pNL1
pNLT
pNLM
Mux
NLMux
f(u)
fNL
0.04228
s2+0.25768s+0.04228
NLdyn
N1
pNH0
pNH1
pNHT
pNHM
Mux
NHMux
f(u)
fNH
0.039033
s2+0.23359s+0.039033
NHdyn
N2
pTE0
pTE1
pTEp
pTEM
Mux
TEMux
f(u)
fTE
0.015048
s2+0.099046s+0.015048
TEdyn
EGT

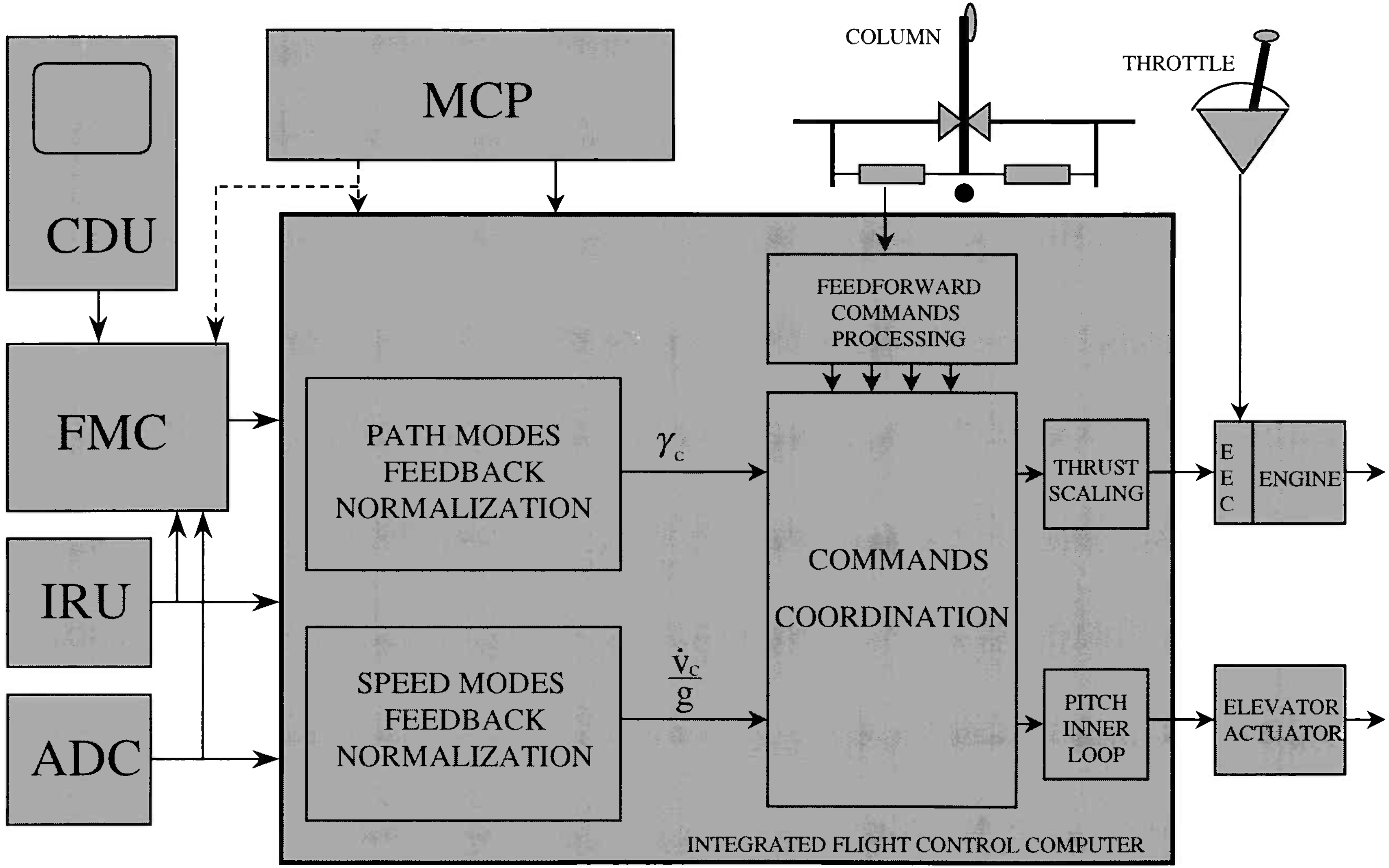

1
height
hgteff_flag
atm_hgt
Tsl
dT
hif
Mux
TcMux
f(u)
Tcalc
Ttrop
Tif
Tsl
Ttrop
dT
psl
g
R
htrop
Mux
pcMux
f(u)
pcalc
f(u)
ptrop
pif
R
rhosl
Mux
TMux
f(u)
rhocalc
Mux
MachMux
f(u)
Machcalc
Mux
EASMux
f(u)
EAScalc
Mux
CASMux
f(u)
CAScalc
p
press
rho
rho
T
temp
Mach
mach
EAS
CAS
2
Vtas


5
qthr
1
Vdot
g
Mux
dVMux
f(u)
Vdot/g
4
theta
ptaugam1
ptaugam2
Mux
tgMux
f(u)
tau_gamma
In
tau
(tau)s
(tau)s+1
theta washout
3
fpa
sin
sin_gam
2
Vtas
pfpa
qfpa
du/dt
dpfpa
In
tau
1
(tau)s+1
lpfdpfpa
du/dt
dtw
Mux
dtwMux
f(u)
fcf
1
2.5s+1
lpf_fc
fcSum
tpfpaSum
fc
Mux
tpfpaMux
2
fcGain
tau_pfpa
f(u)
tpfpaFun
1
s
tpfpa
qpfpa
qVdot/g
Vdot/g quickened
qhdot
hdot quickened

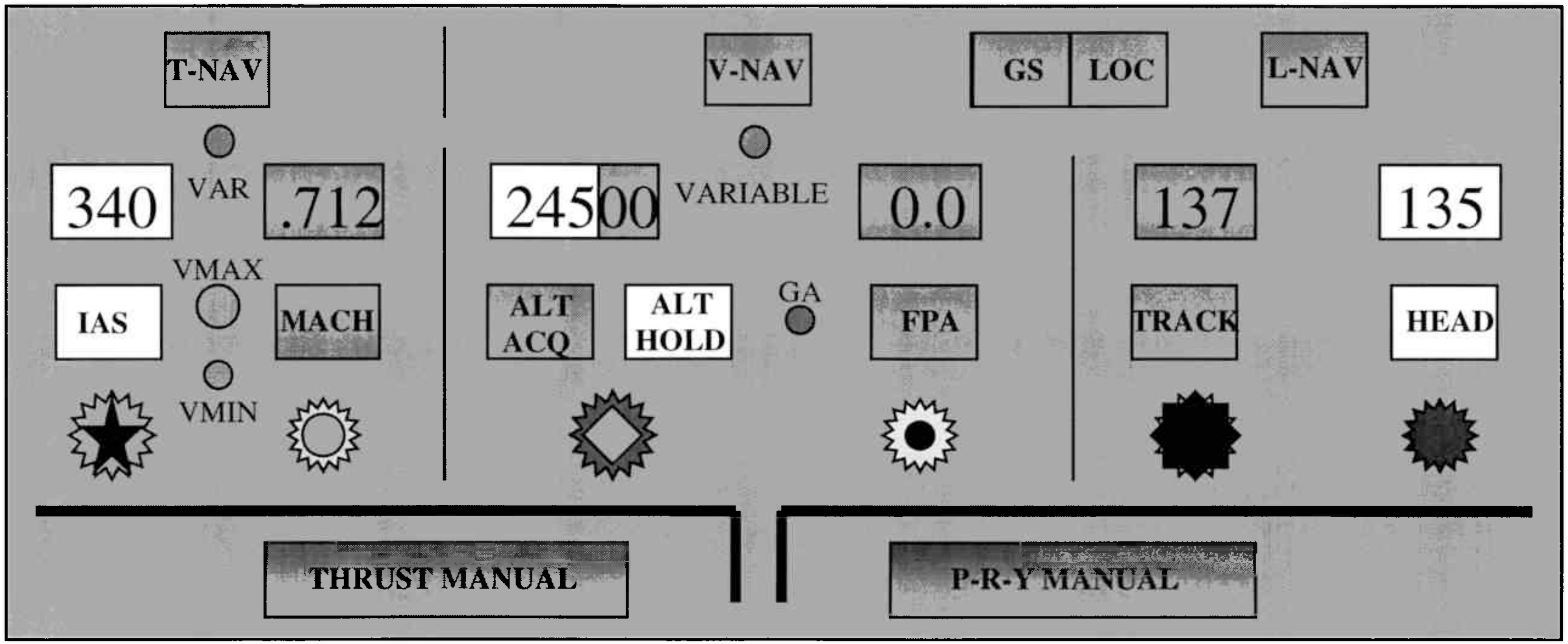
Appendix J

Powerpoint sheets from ir. A.A. Lambregts

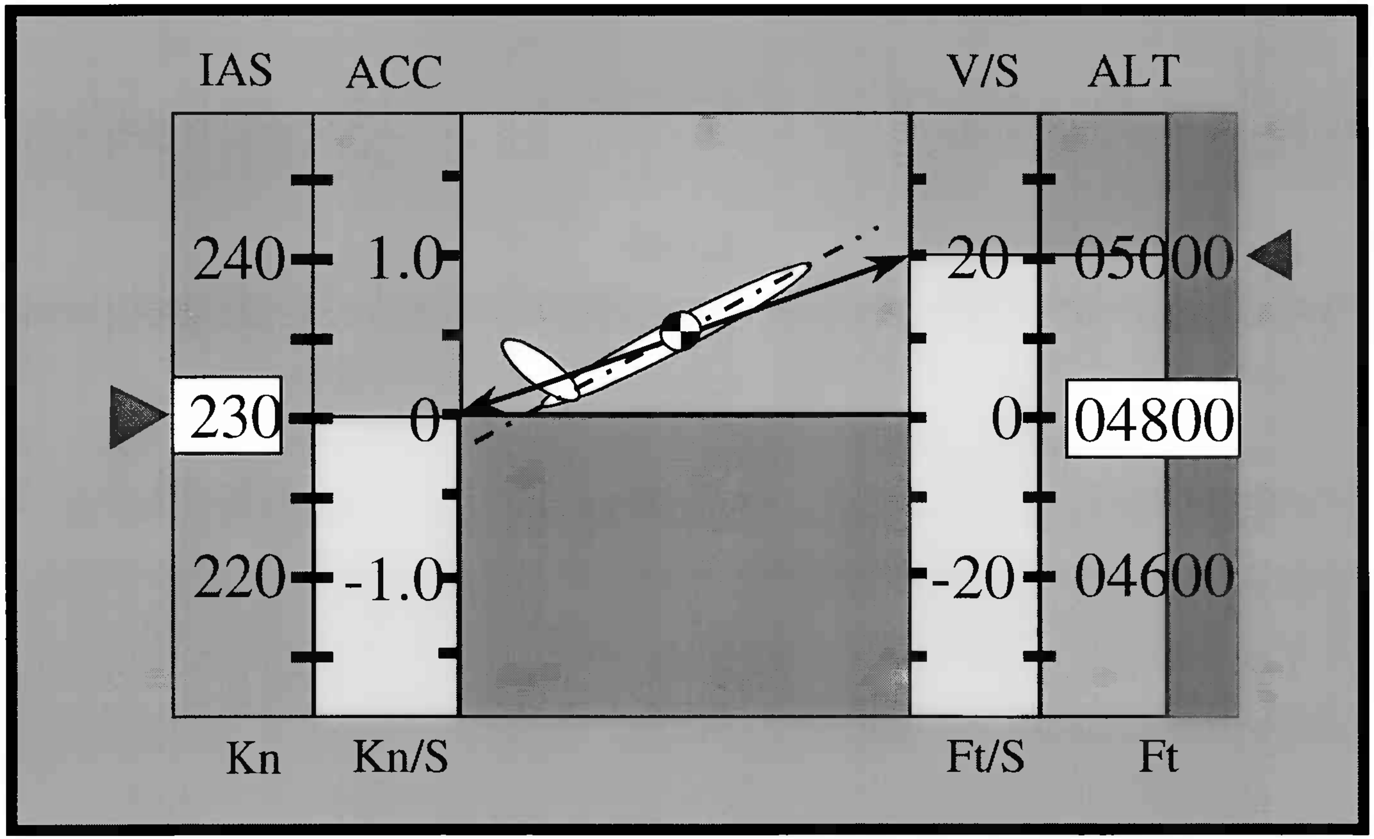
TECS FUNCTIONAL ARCHITECTURE



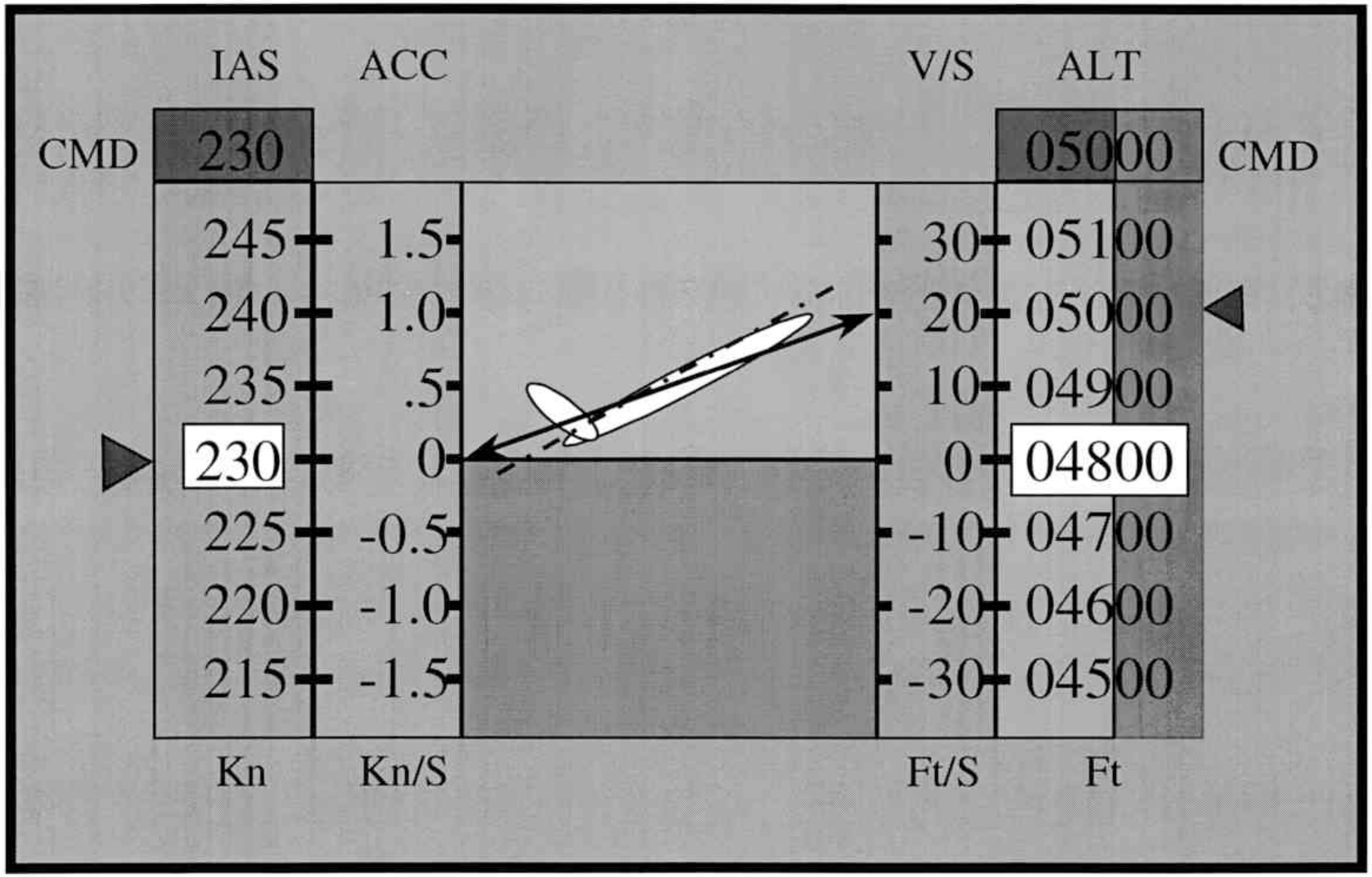
Mode Control Panel with Hierarchical Function Arrangement



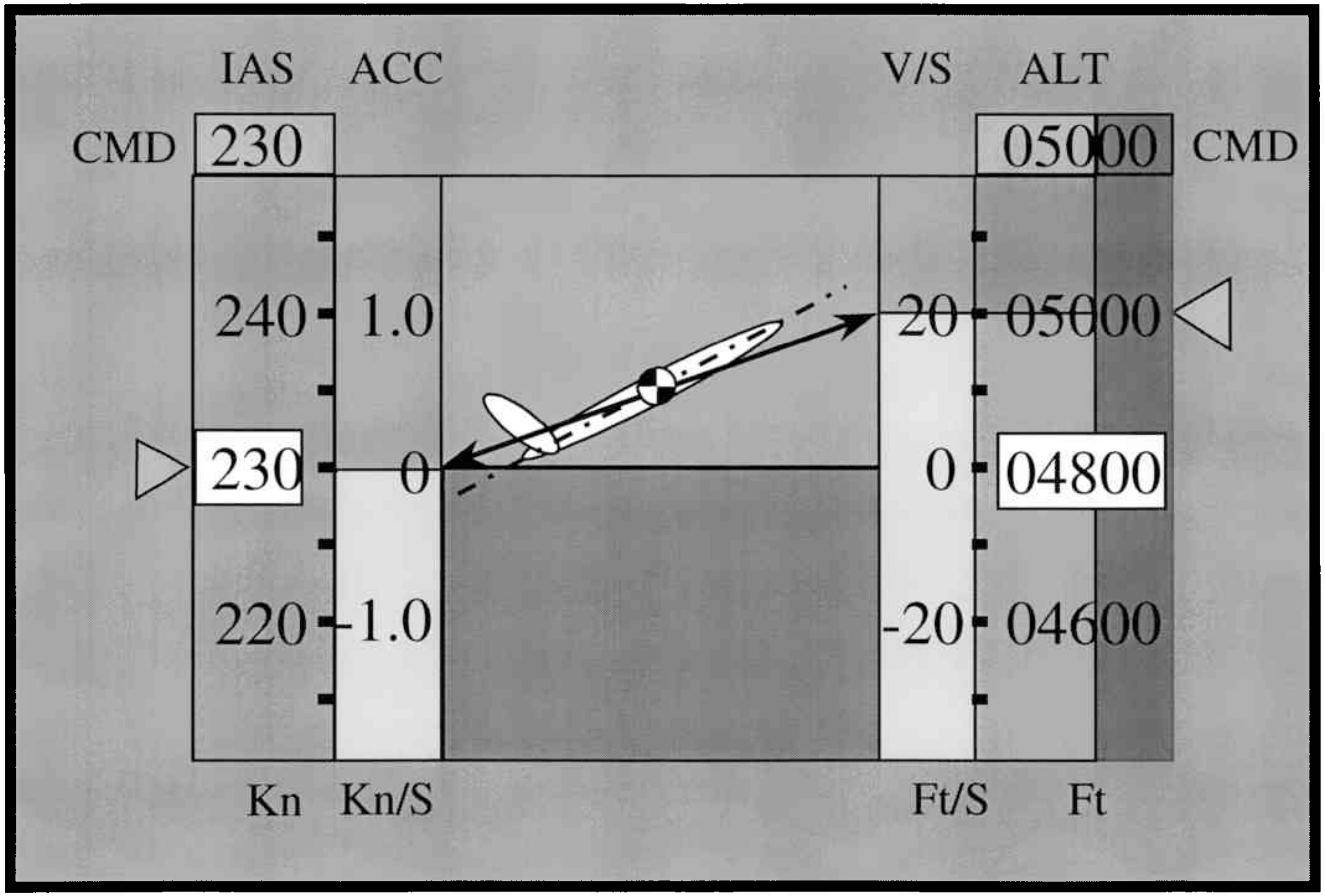
GENERALIZED FLIGHT CONTROL DISPLAY



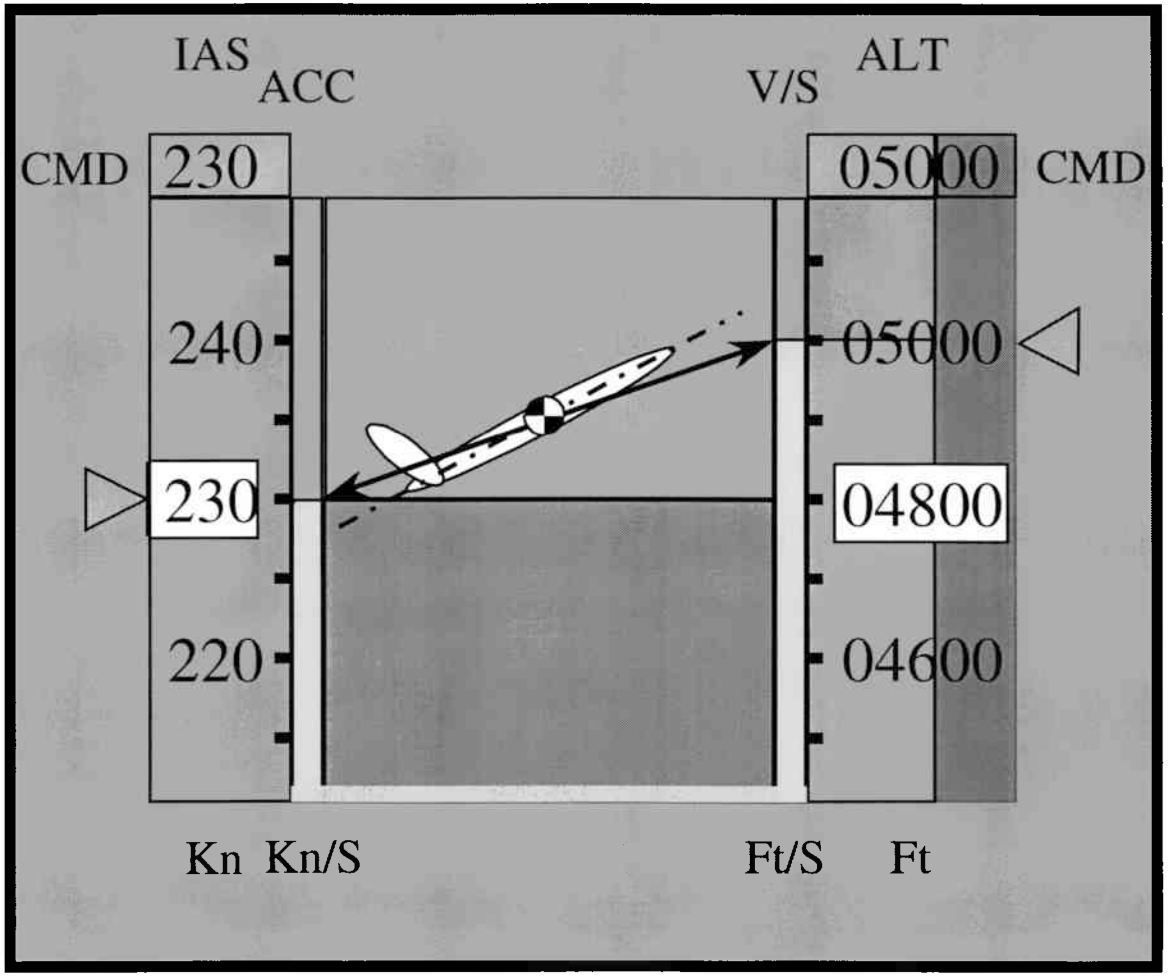
ENERGY MANAGEMENT FLIGHT CONTROL DISPLAY



ENERGY MANAGEMENT FLIGHT CONTROL DISPLAY

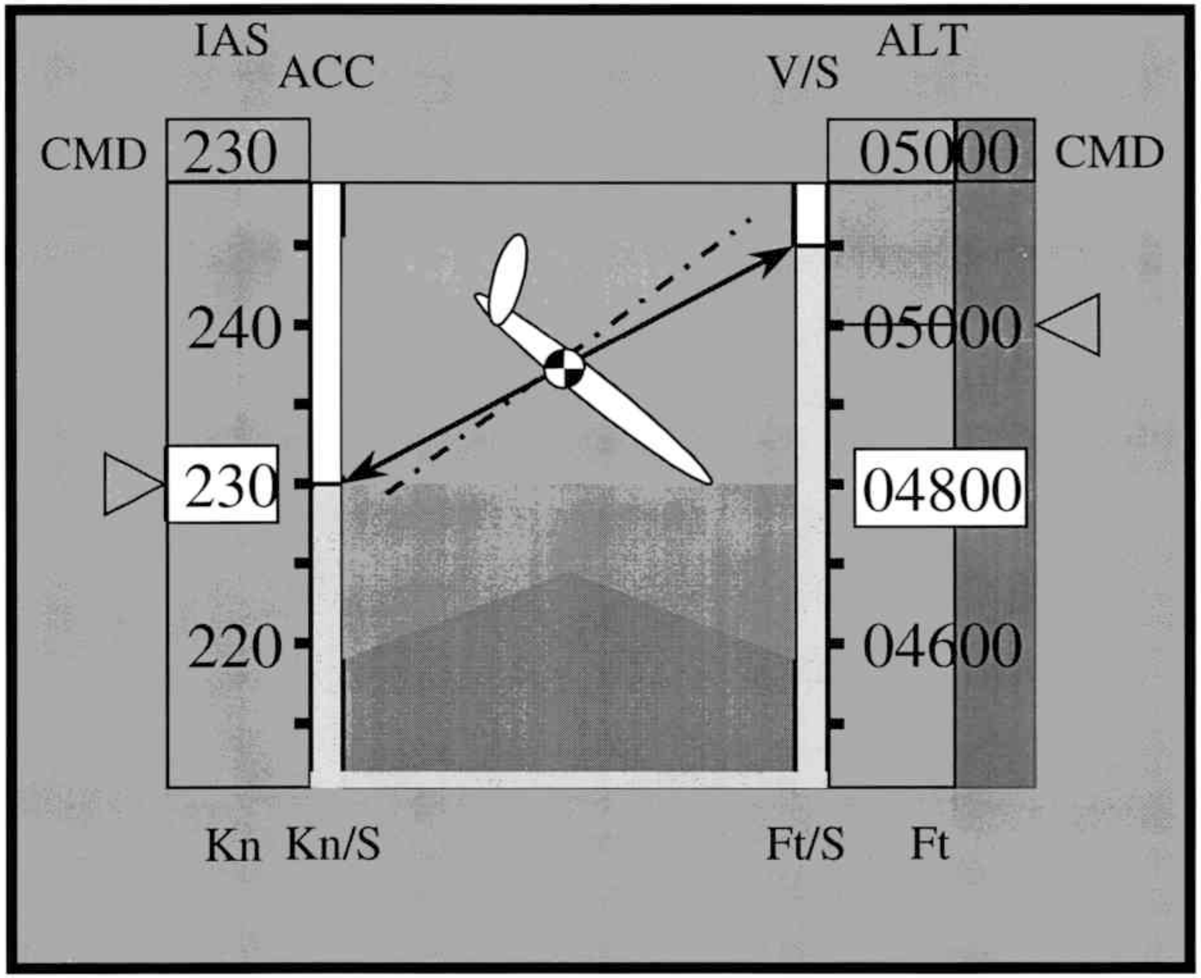


ENERGY MANAGEMENT / FLIGHT CONTROL DISPLAY



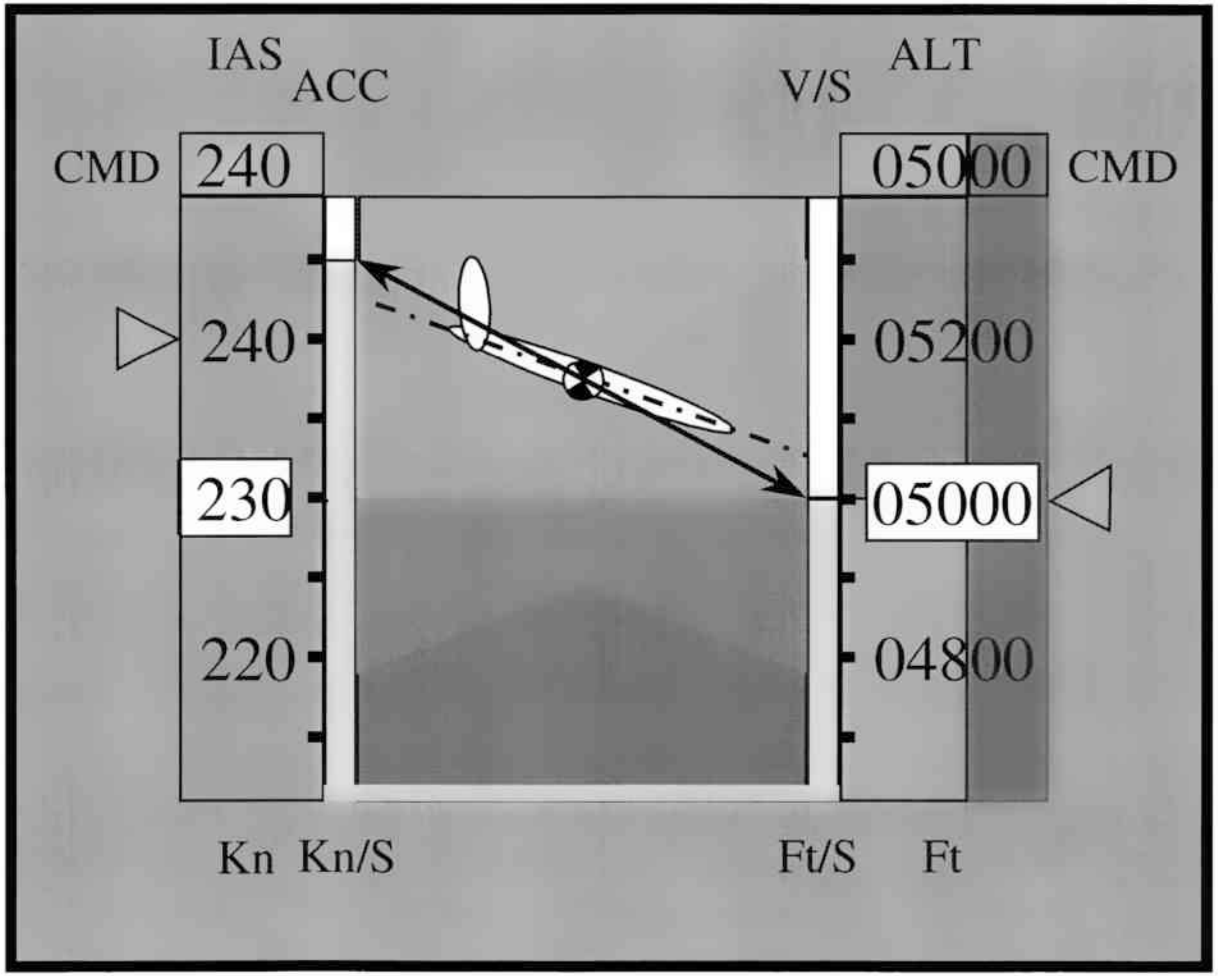
Altitude Capture - Constant Speed

ENERGY MANAGEMENT / FLIGHT CONTROL DISPLAY



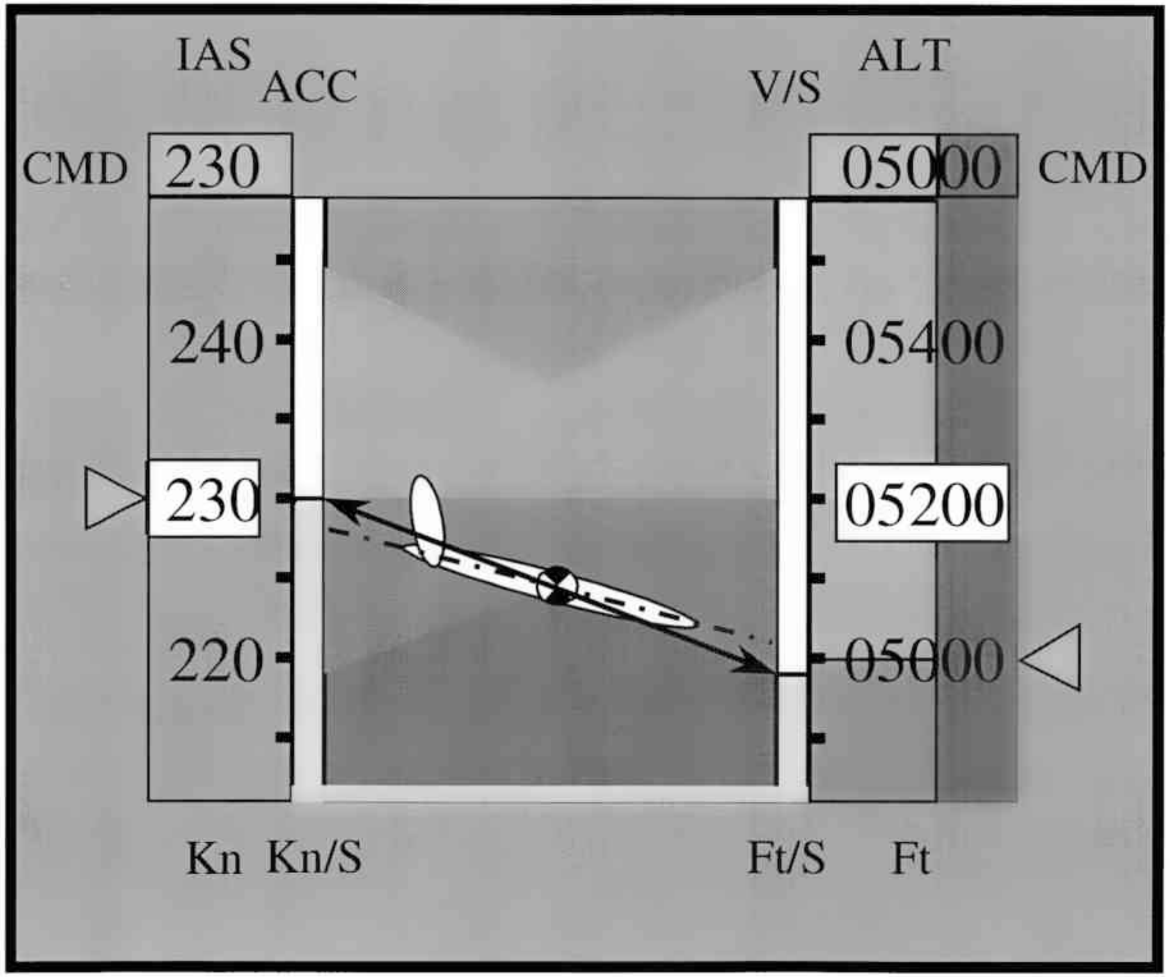
Max Thrust Climb - Constant Speed

ENERGY MANAGEMENT / FLIGHT CONTROL DISPLAY



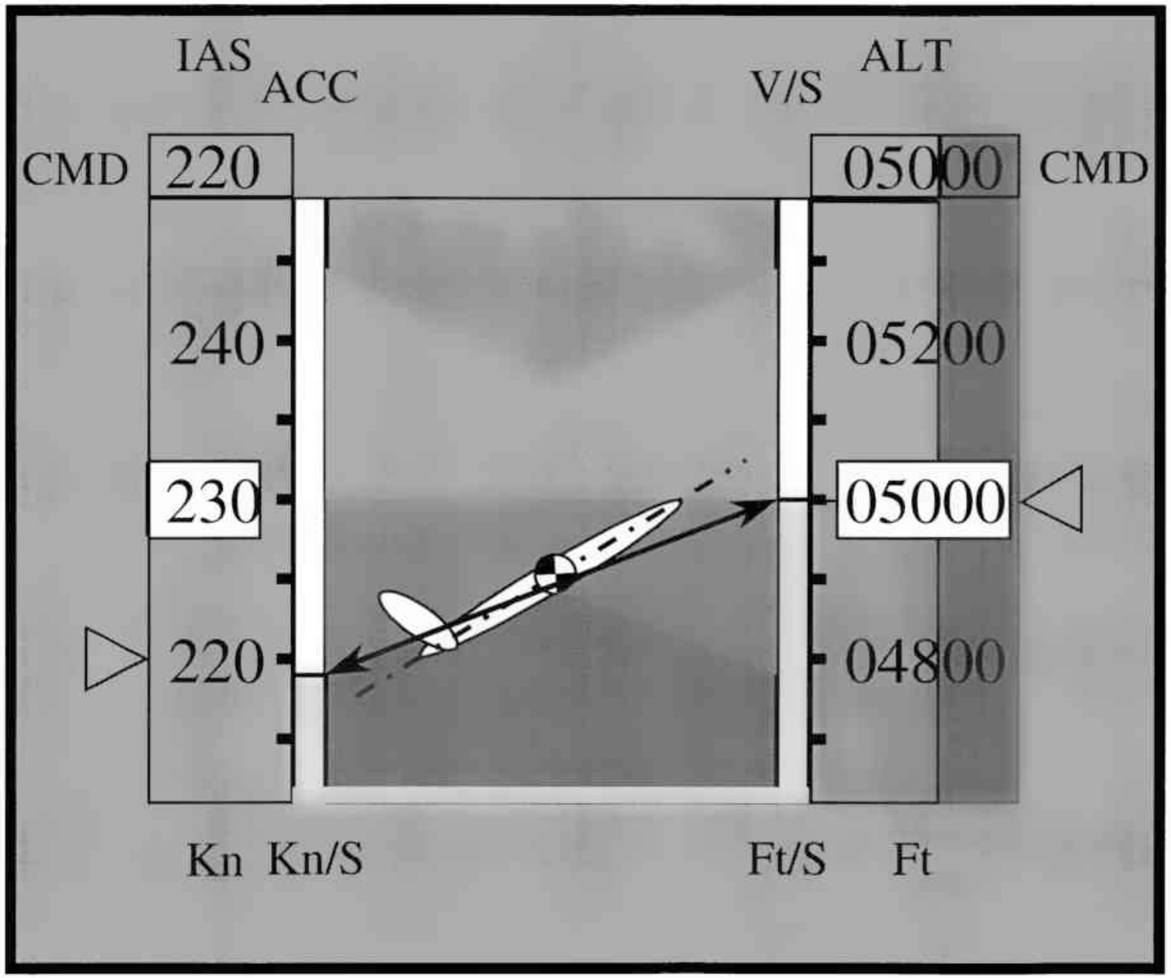
Max Thrust Accelerate- Constant Altitude

ENERGY MANAGEMENT / FLIGHT CONTROL DISPLAY



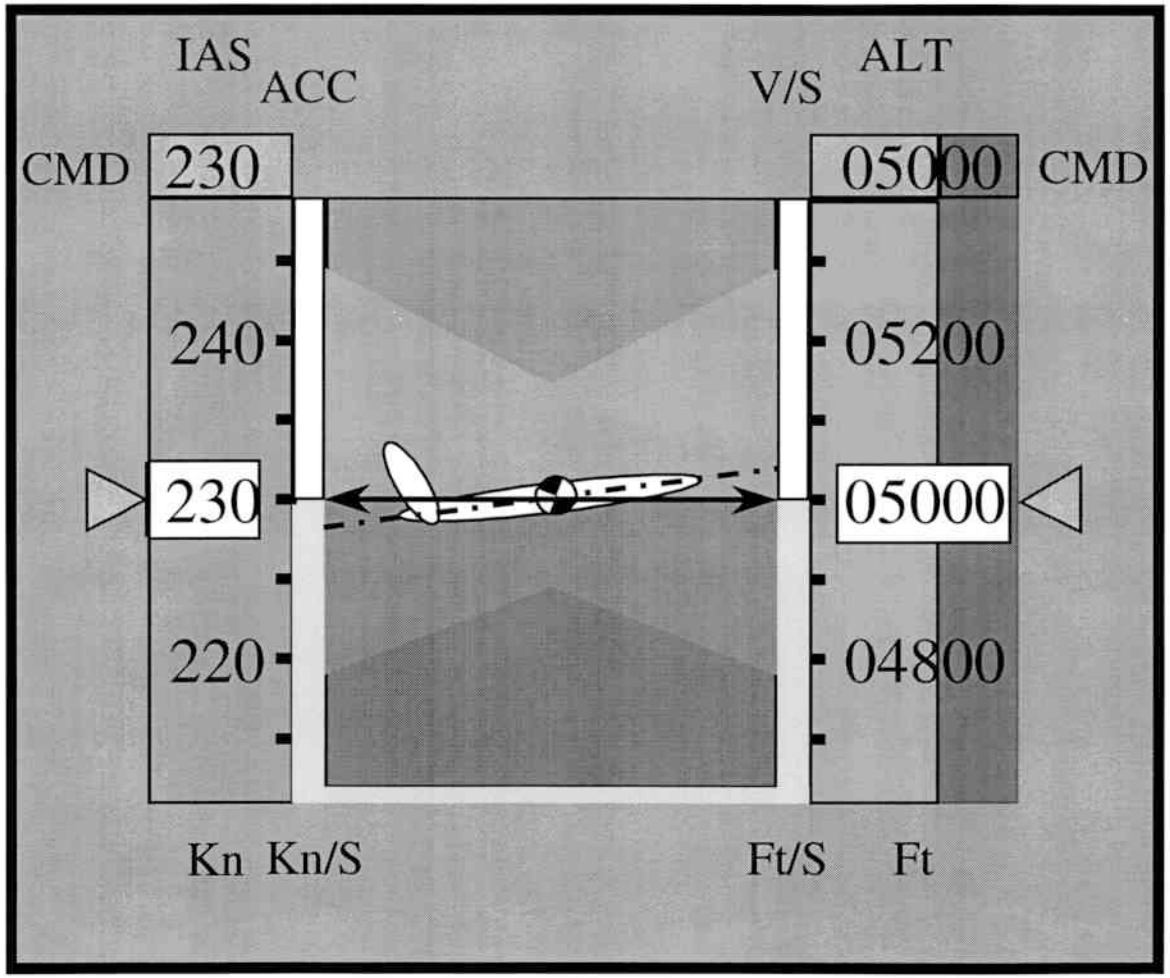
Mid Speed - Idle Descent

ENERGY MANAGEMENT / FLIGHT CONTROL DISPLAY



Idle decelerate - Holding Altitude

ENERGY MANAGEMENT / FLIGHT CONTROL DISPLAY



Mid Speed - Trimmed Level

BALANCING FLIGHT PATH AND SPEED CONTROL IN TURBULENCE AND WINDSHEAR

- **control bandwidth for changing energy state is strictly determined by engine response and allowable throttle activity**

- **the frequency and magnitude of energy variation due to turbulence can far exceed energy control bandwidth - forcing short term energy errors to be distributed between altitude or speed**

- **traditional autopilots and autothrottles were designed empirically, without a good understanding of flight path and speed control interactions**

- **proper balancing of altitude / speed tracking and control activity in turbulence requires suitable design and correct turbulence modeling /analyses**

- **options for balancing altitude and speed tracking performance in turbulence:**
    - **synthesis of feedback signals by frequency dependent blending of inertial and airmass referenced states**
    - **for pitch controller: the choice of innerloop feedbacks**
    - **choice of altitude and speed control bandwidths (not good option)**

FEEDBACK SIGNAL SYNTHESIS

airmass referenced signals	blended	inertially referenced signals
air speed	V	**inertial speed**
airspeed rate	$\dot{V}$	**inertial acceleration**
baro altitude	h	**geodesic altitude**
baro altitude rate	$\dot{h}$	**geodesic altitude rate**
---	$\ddot{h}$	**vertical acceleration**
angle of attack	α	**inertial angle of attack =**
---	$\dot{\alpha}$	**inertial angle of attack rate**
sideslip	β	**inertial sideslip = drift angle**
---	$\dot{\beta}$	**inertial sideslip rate**
vertical airmass flight path angle	γ	**vertical inertial flight path angle**
---	$\dot{\gamma}$	---

FEEDBACK SIGNAL SYNTHESIS

COMPLEMENTARY FILTERS

FIRST ORDER

$$\frac{\tau s+1}{\tau s+1} = \frac{\tau s}{\tau s+1} + \frac{1}{\tau s+1}$$

SECOND ORDER

$$\frac{K_2S^2+K_1S+1}{K_2S^2+K_1S+1} = \frac{K_2S}{K_2S^2+K_1S+1} + \frac{K_1S+1}{K_2S^2+K_1S+1}$$

$$= \frac{K_2S^2+S}{K_2S^2+K_1S+1} + \frac{1}{K_2S^2+K_1S+1}$$

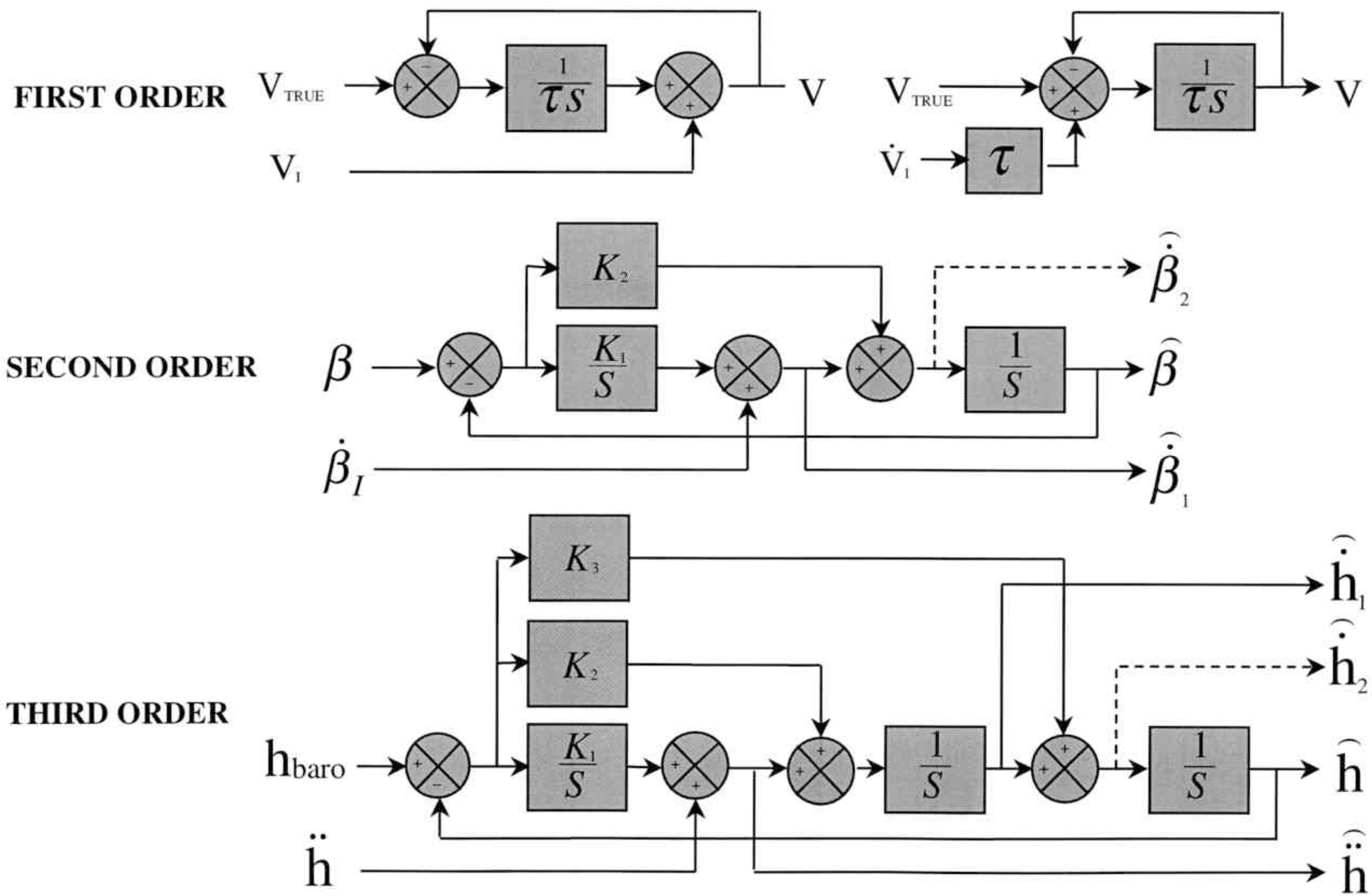
THIRD ORDER

$$\frac{K_3S^3+K_2S^2+K_1S+1}{K_3S^3+K_2S^2+K_1S+1} = \frac{K_3S^3}{K_3S^3+K_2S^2+K_1S+1} + \frac{K_2S^2+K_1S+1}{K_3S^3+K_2S^2+K_1S+1}$$

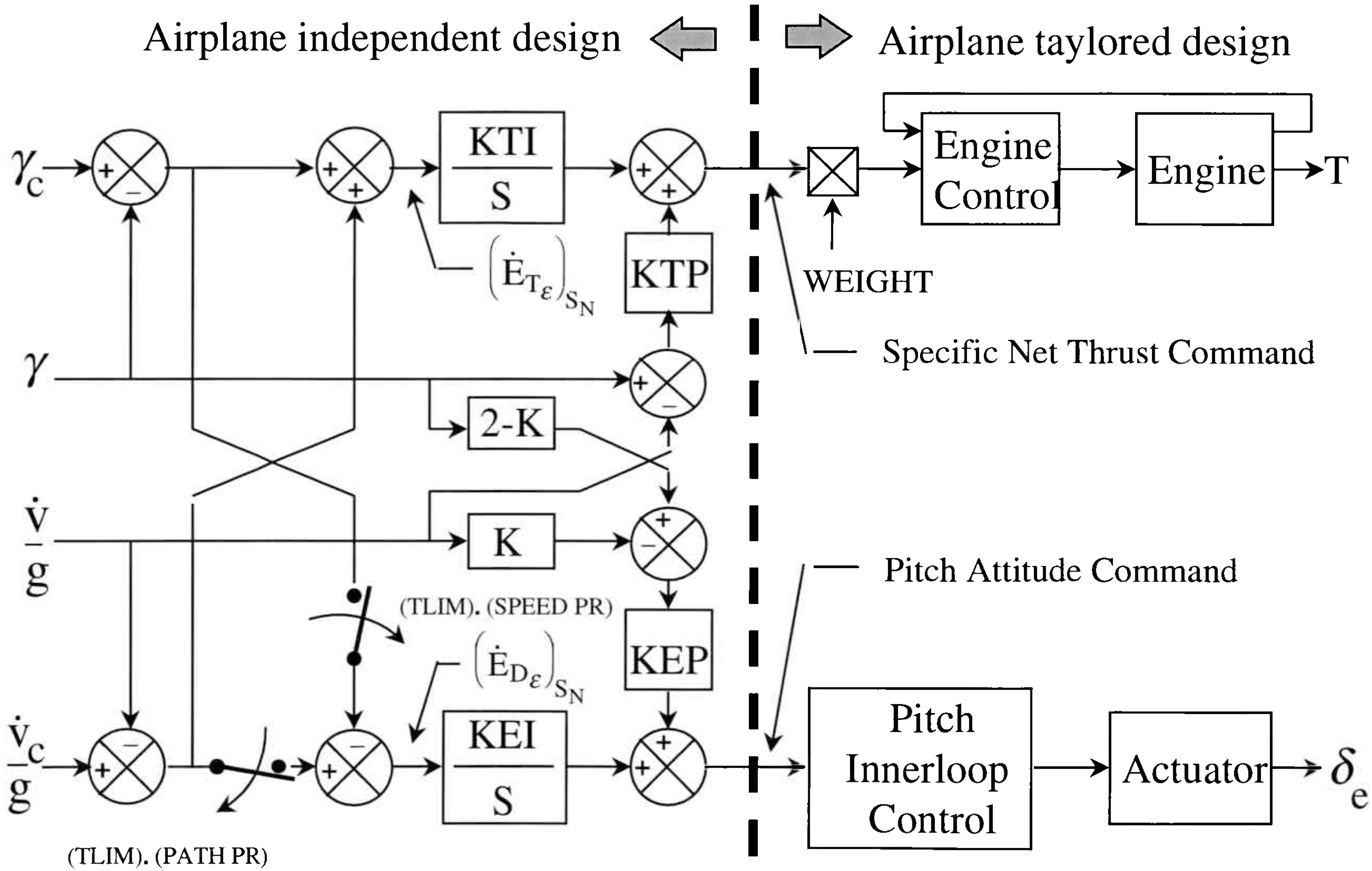
$$= \frac{K_3S^3+K_2S^2}{K_3S^3+K_2S^2+K_1S+1} + \frac{K_1S+1}{K_3S^3+K_2S^2+K_1S+1}$$

FEEDBACK SIGNAL SYNTHESIS

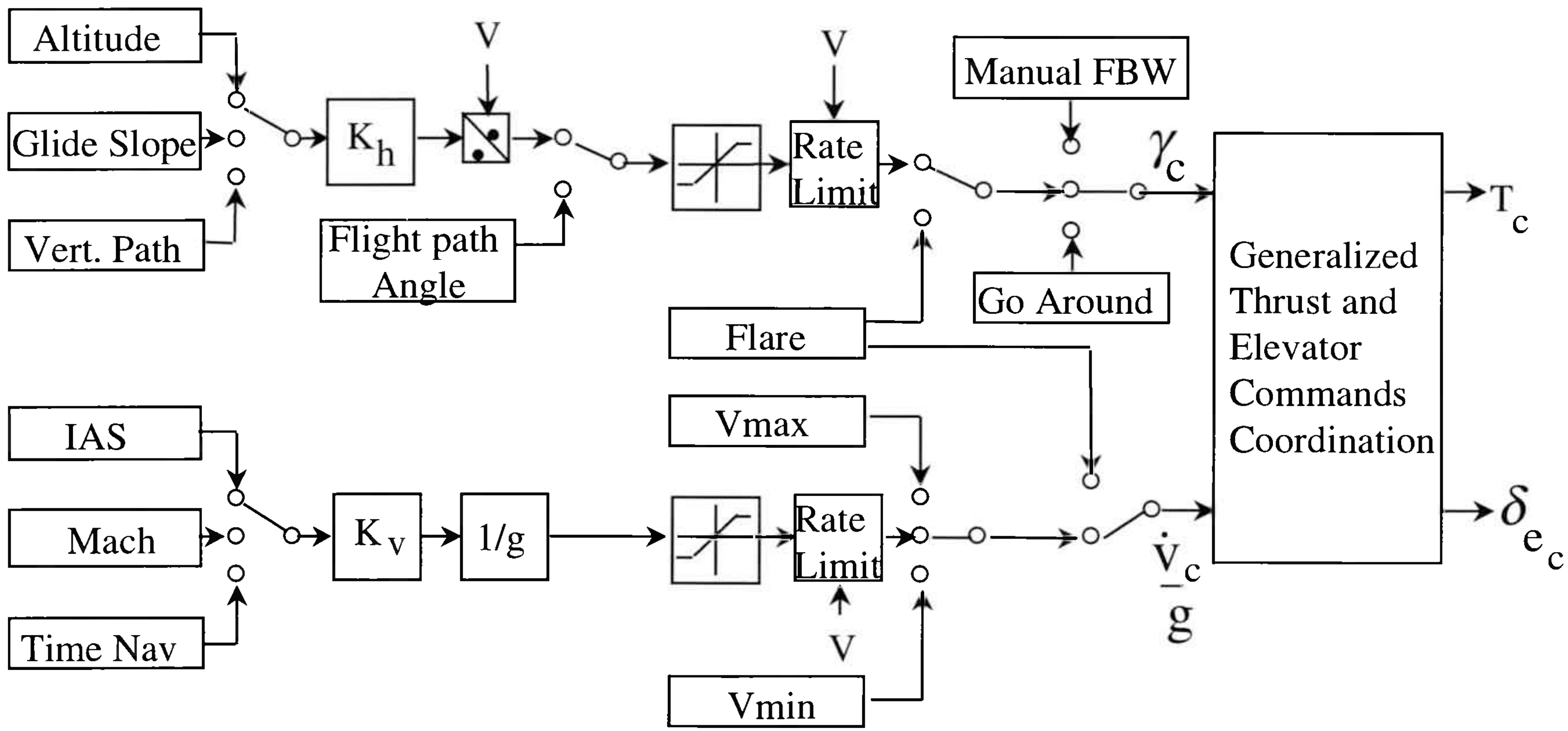
COMPLEMENTARY FILTERS



Total Energy Control System
Core Algorithm

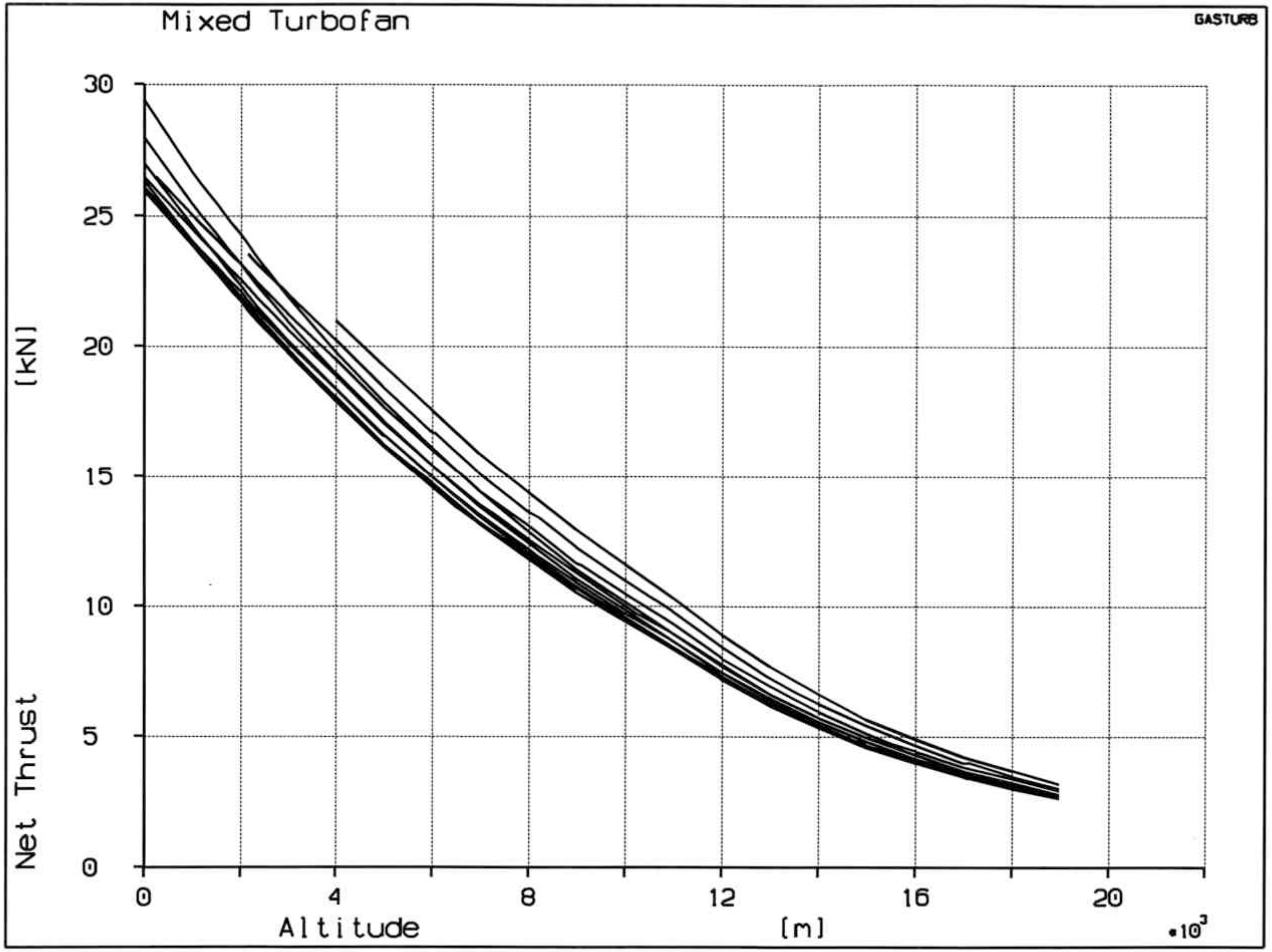


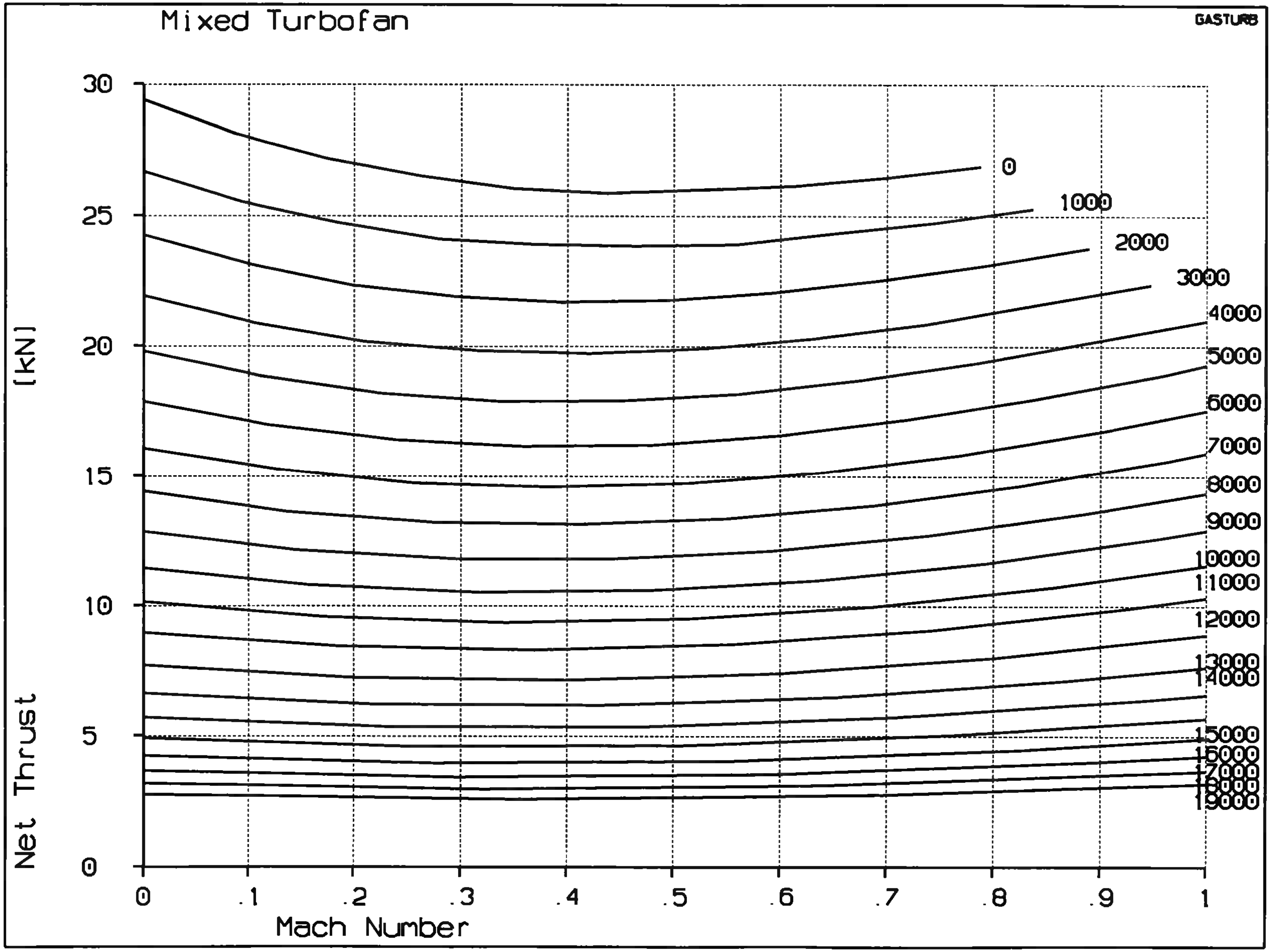
TECS Architecture and Mode Hierarchy



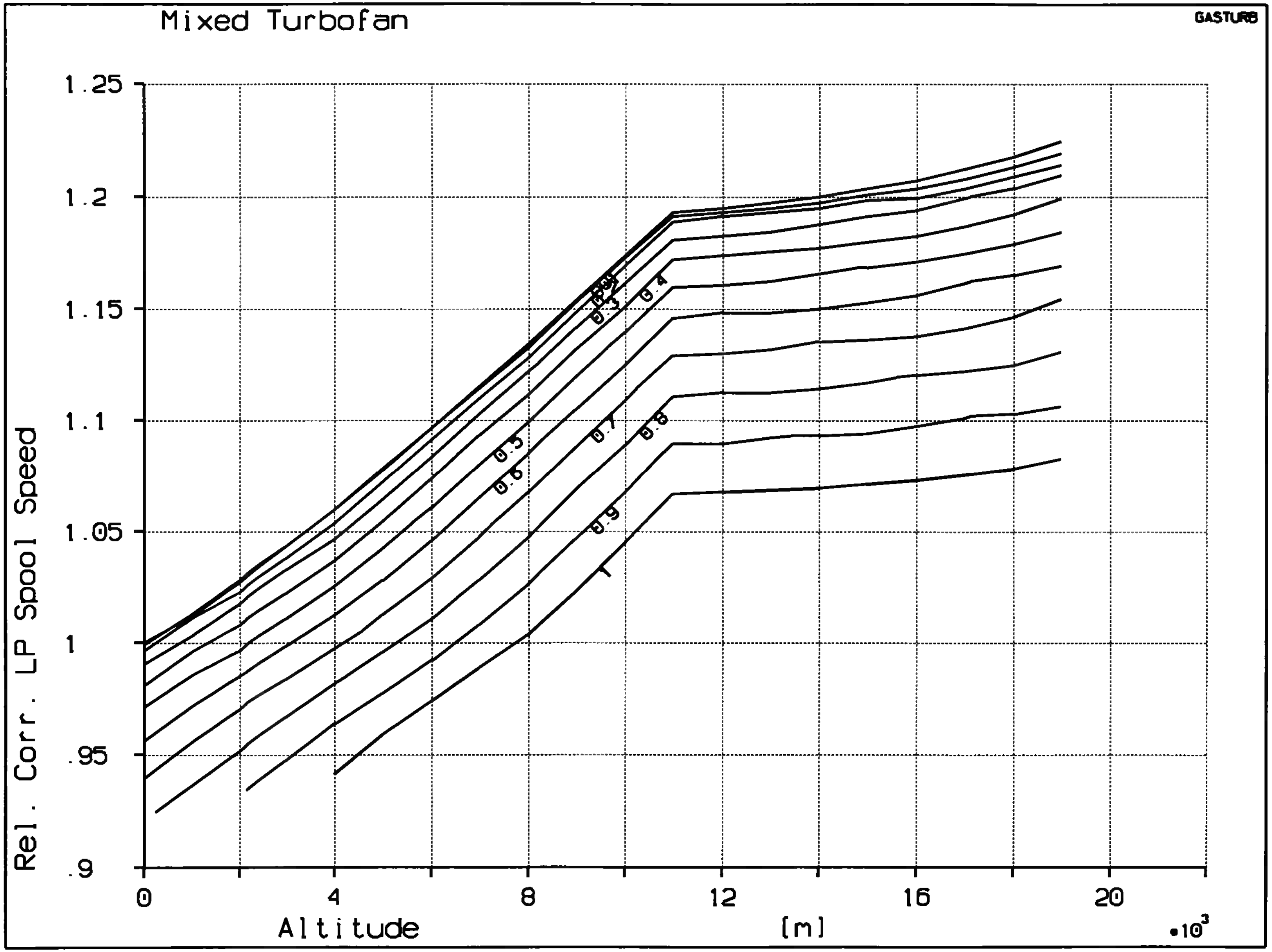
Appendix K

Engine graphs of gasturbine simulator GASTURB

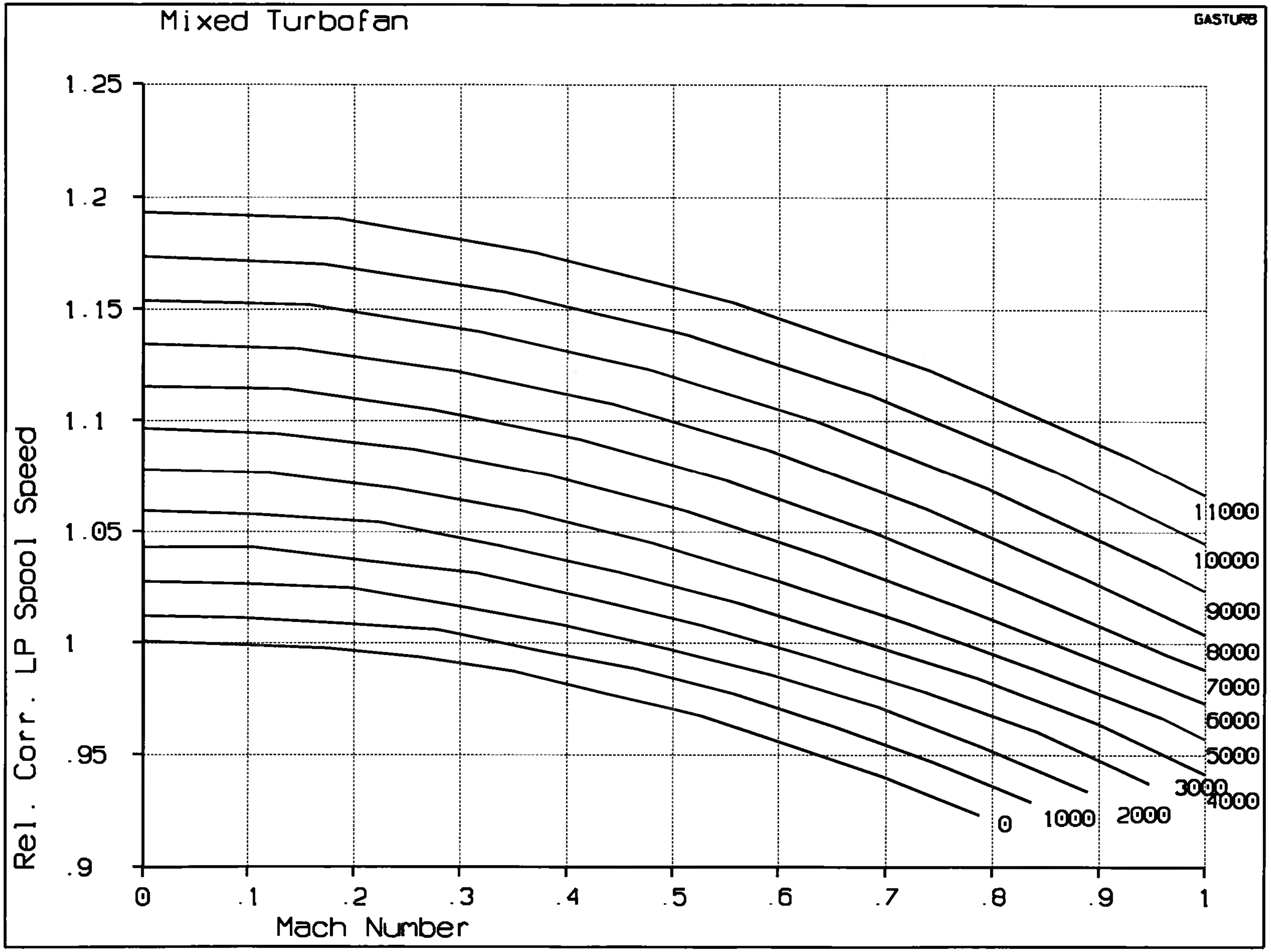

Mixed Turbofan
GASTURB
30
25
20
15
10
5
0
Net Thrust [kN]
0
4
8
12
16
20
Altitude [m]
*10^3



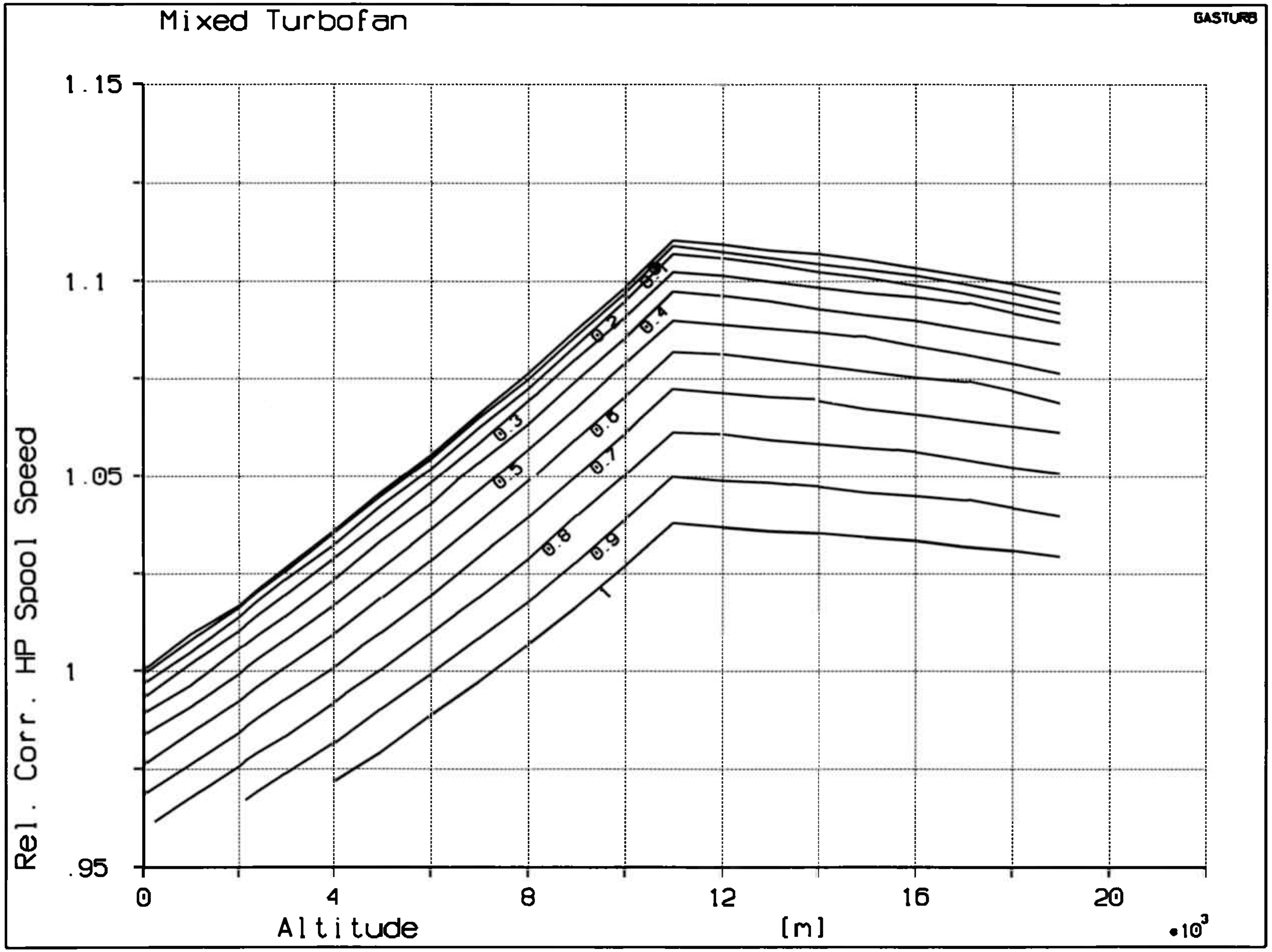
Mixed Turbofan
GASTURB
Net Thrust [kN]
Mach Number
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000

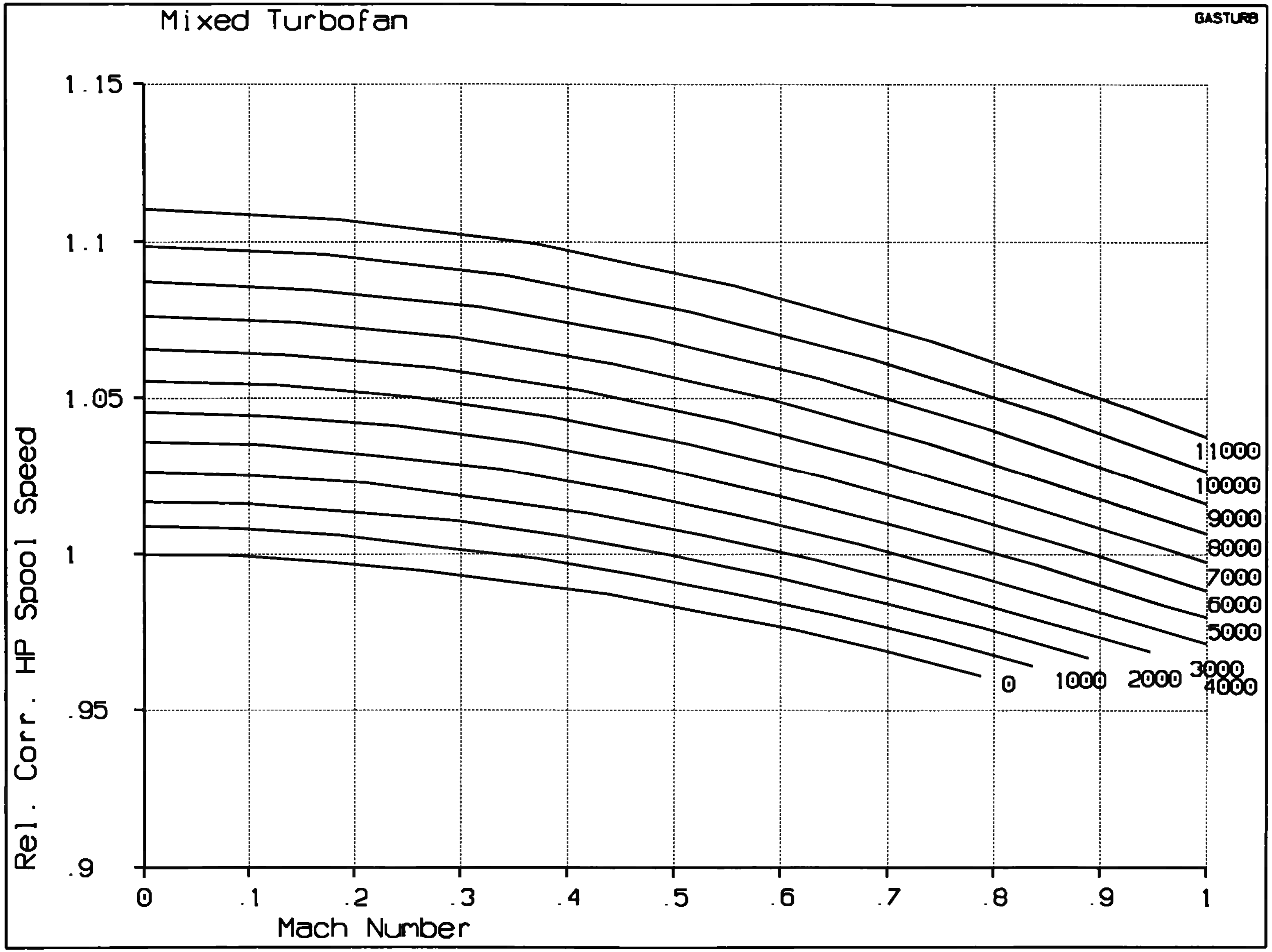


Mixed Turbofan
GASTURB
Rel. Corr. LP Spool Speed
1.25
1.2
1.15
1.1
1.05
1
.95
.9
0
4
8
12
16
20
Altitude
[m]
•10³
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

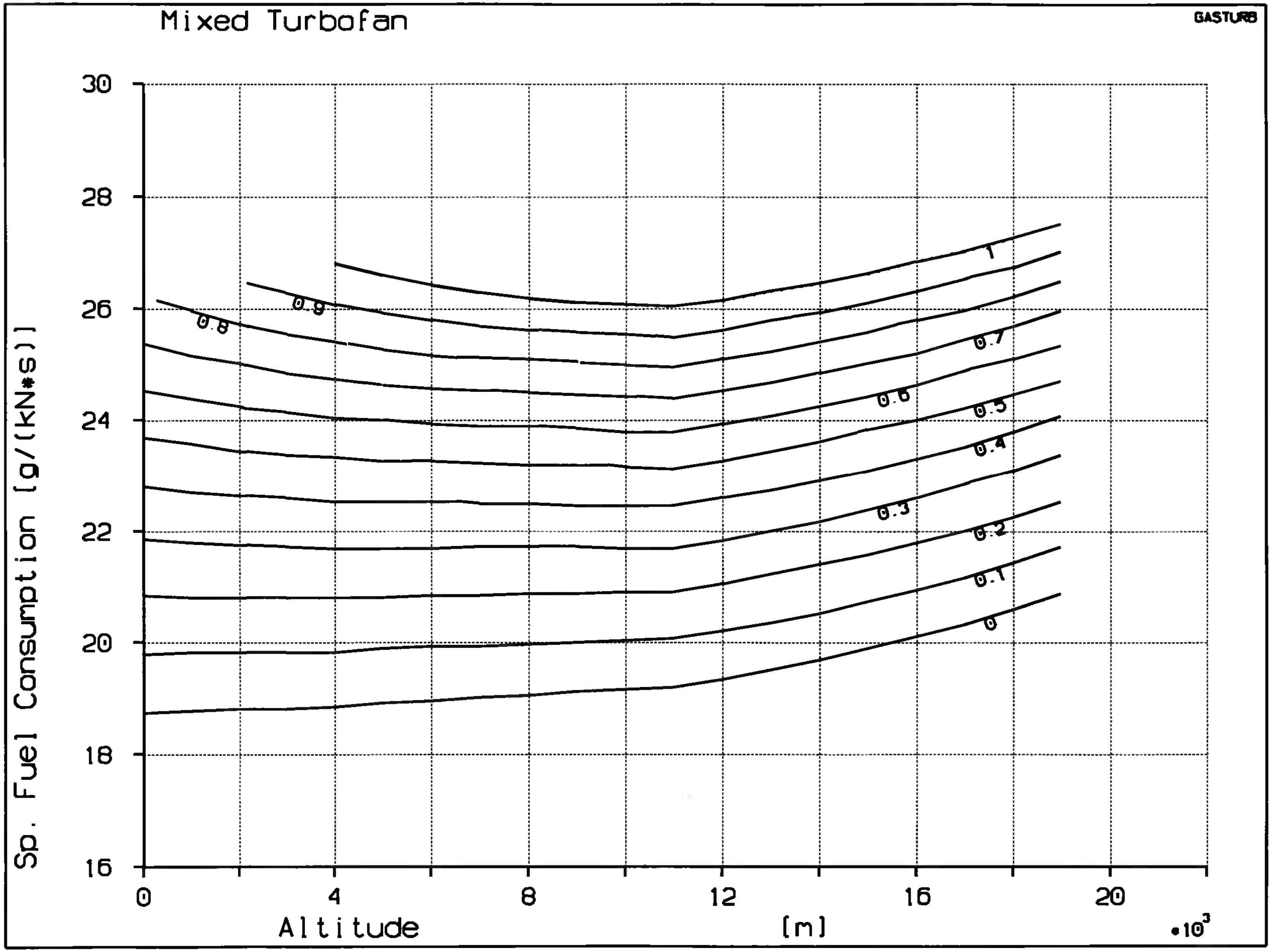


Mixed Turbofan
GASTURB
Rel. Corr. LP Spool Speed
1.25
1.2
1.15
1.1
1.05
1
.95
.9
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
Mach Number
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0

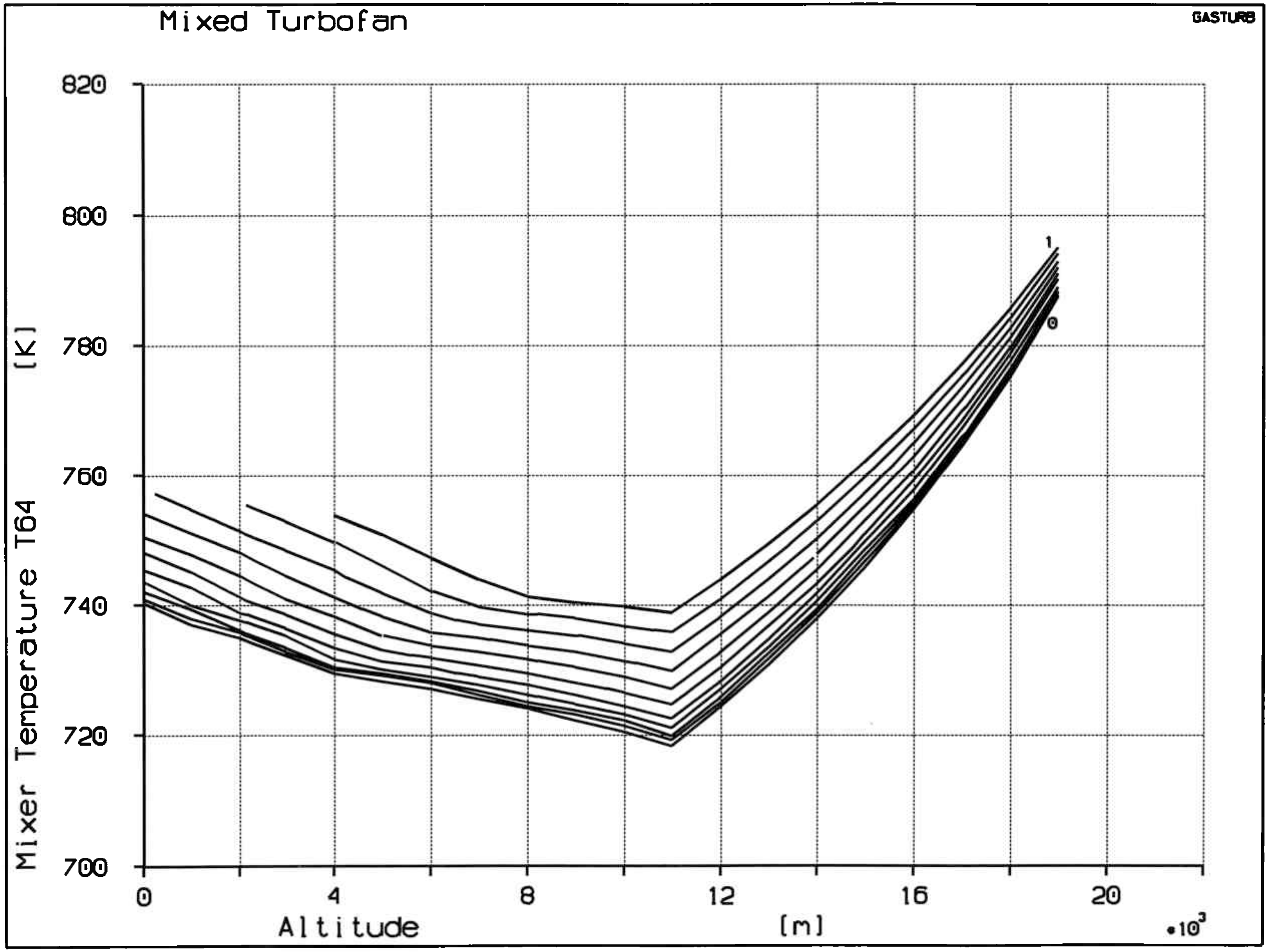

Mixed Turbofan
GASTURB
1.15
1.1
1.05
1
.95
Rel. Corr. HP Spool Speed
0
4
8
12
16
20
Altitude
[m]
•10³
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Mixed Turbofan
GASTURB
Rel. Corr. HP Spool Speed
1.15
1.1
1.05
1
.95
.9
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
Mach Number
11000
10000
9000
8000
7000
6000
5000
3000
4000
2000
1000
0



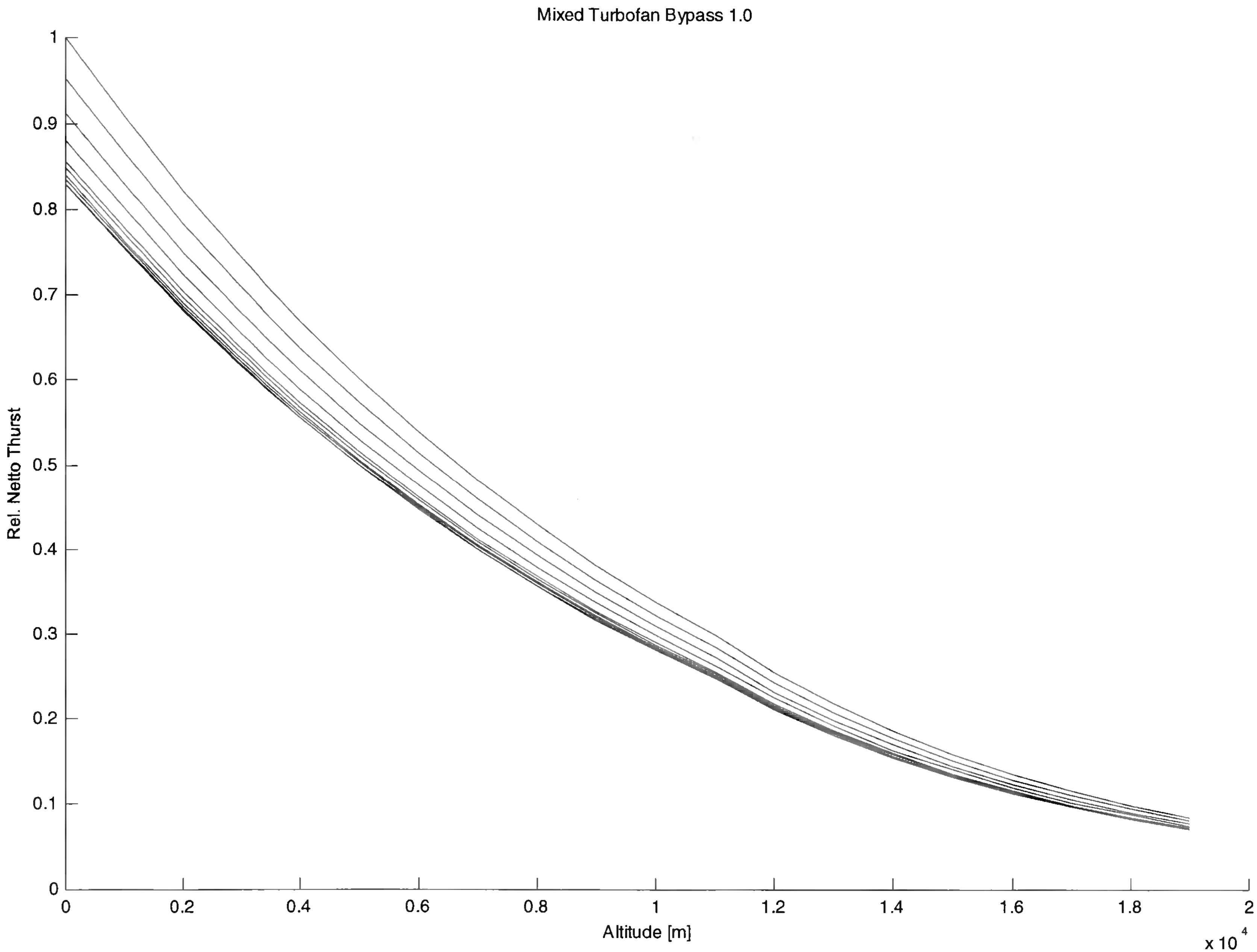
Mixed Turbofan
GASTURB
Sp. Fuel Consumption [g/(kN*s)]
30
28
26
24
22
20
18
16
0
4
8
12
16
20
Altitude
[m]
•10³
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

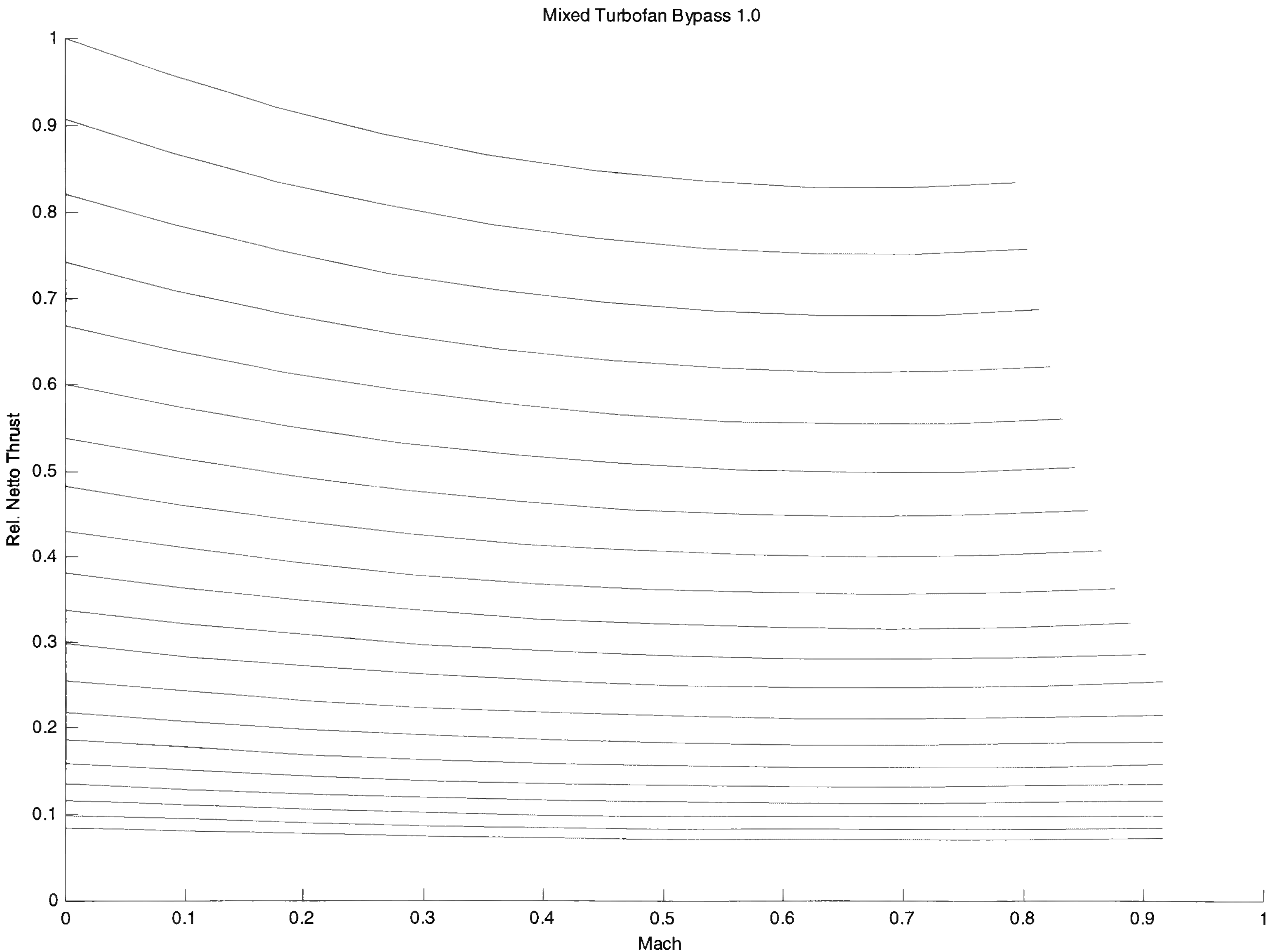


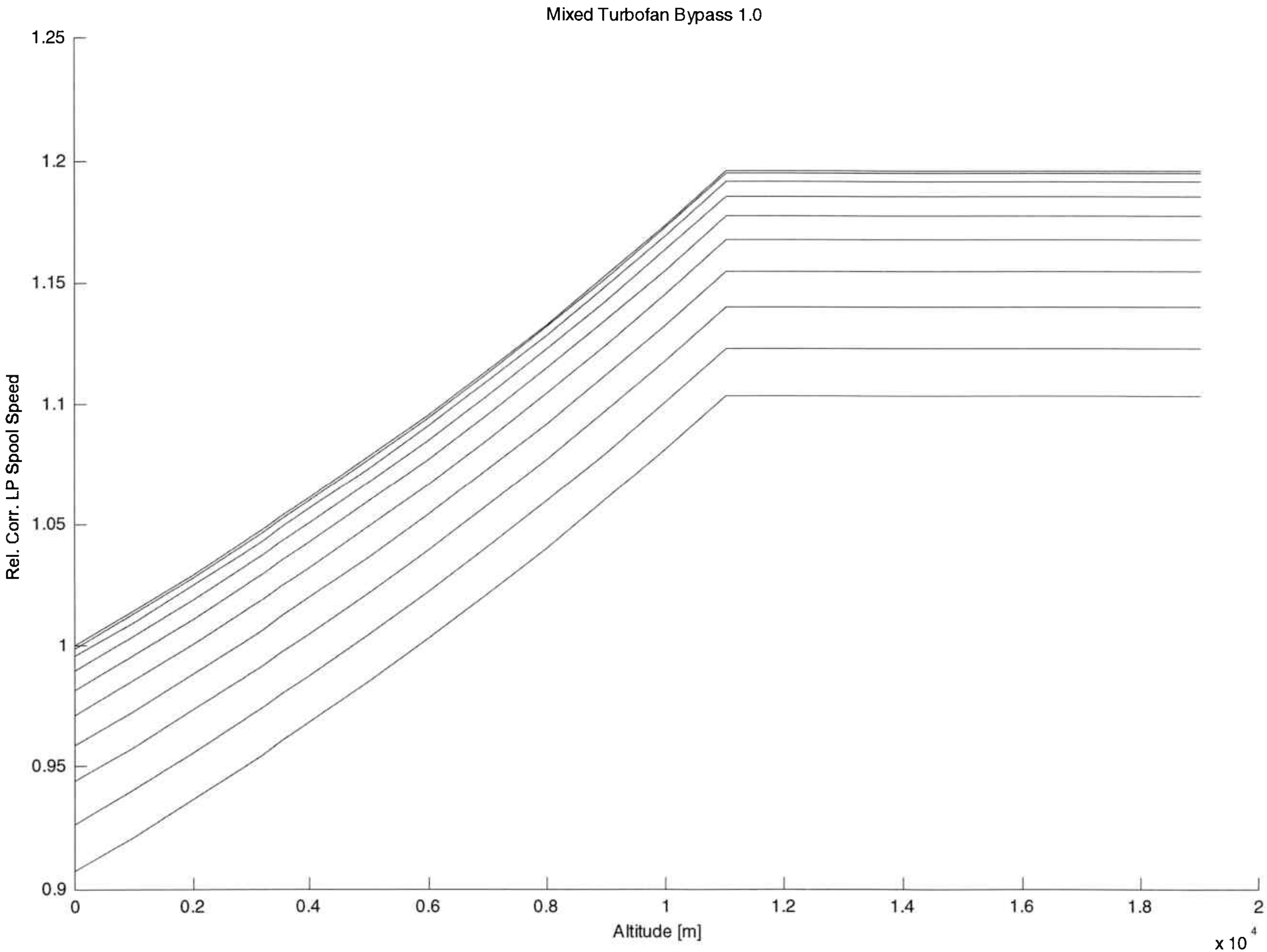
Mixed Turbofan
GASTURB
820
800
780
760
740
720
700
Mixer Temperature T64 [K]
1
0
0
4
8
12
16
20
Altitude
[m]
*10³

Appendix L

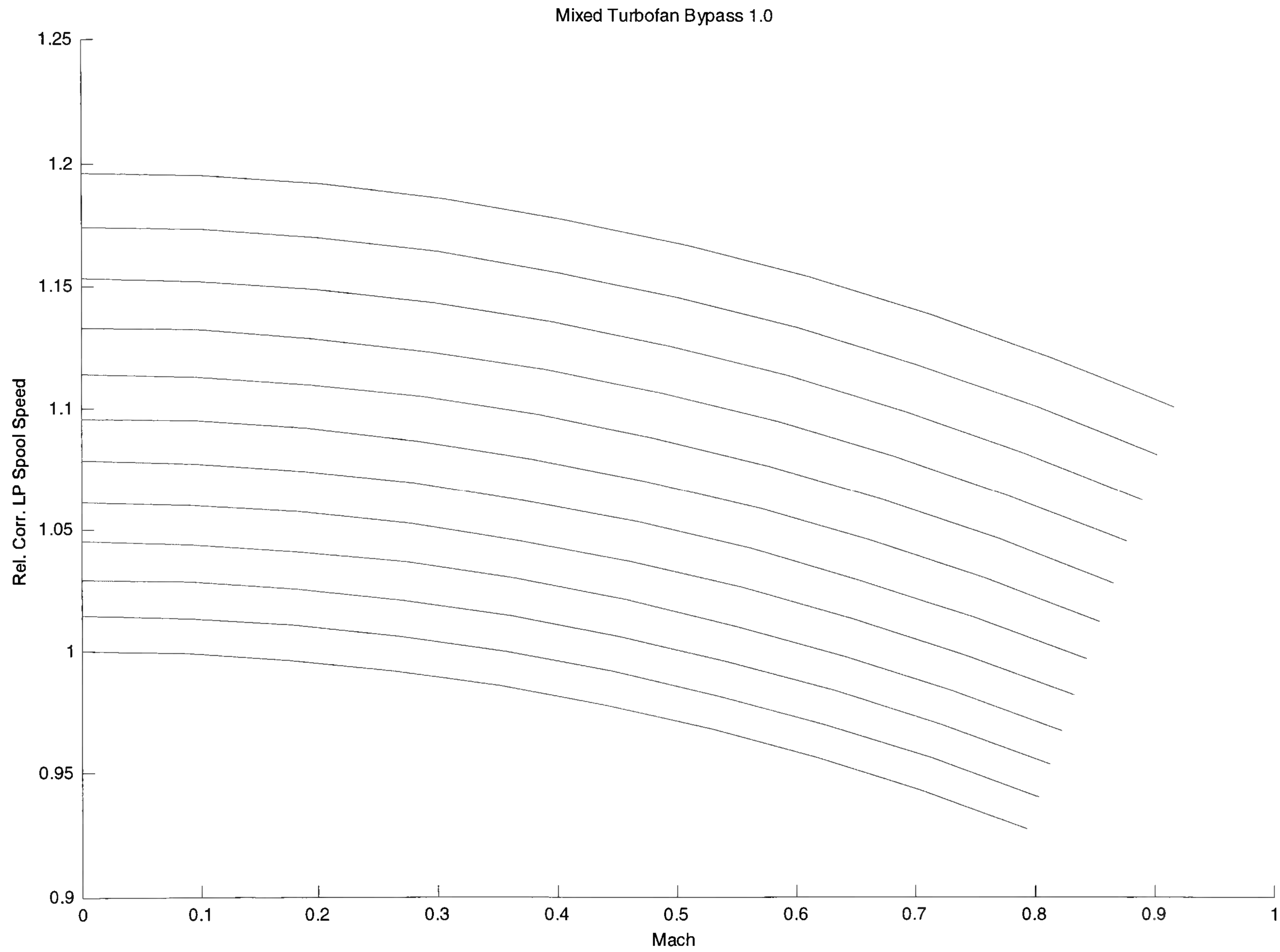
Engine graphs of fitted engine parameters

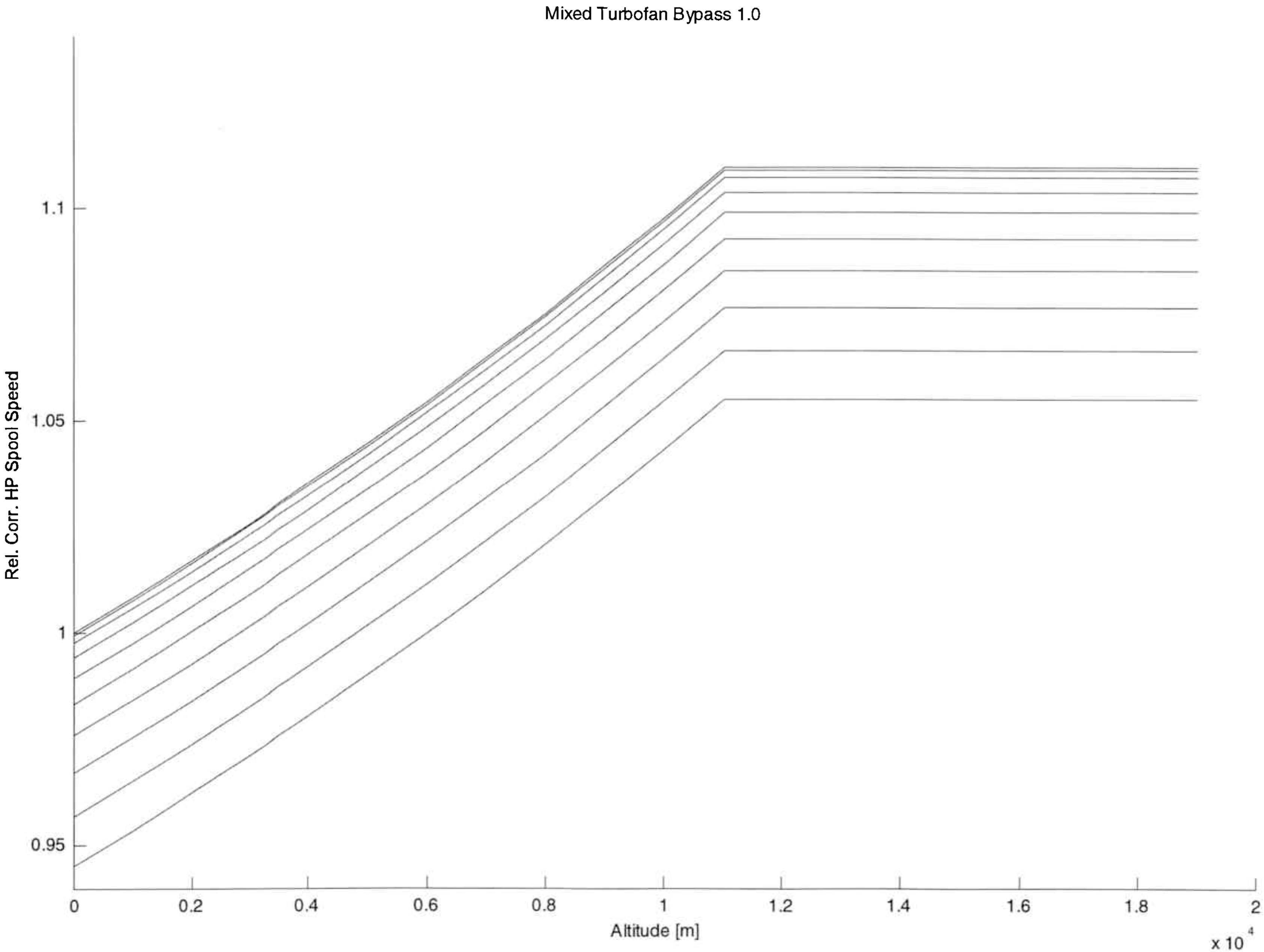

Mixed Turbofan Bypass 1.0
Rel. Netto Thurst
Altitude [m]
x 10^4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8
2


Mixed Turbofan Bypass 1.0
Rel. Netto Thrust
Mach
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

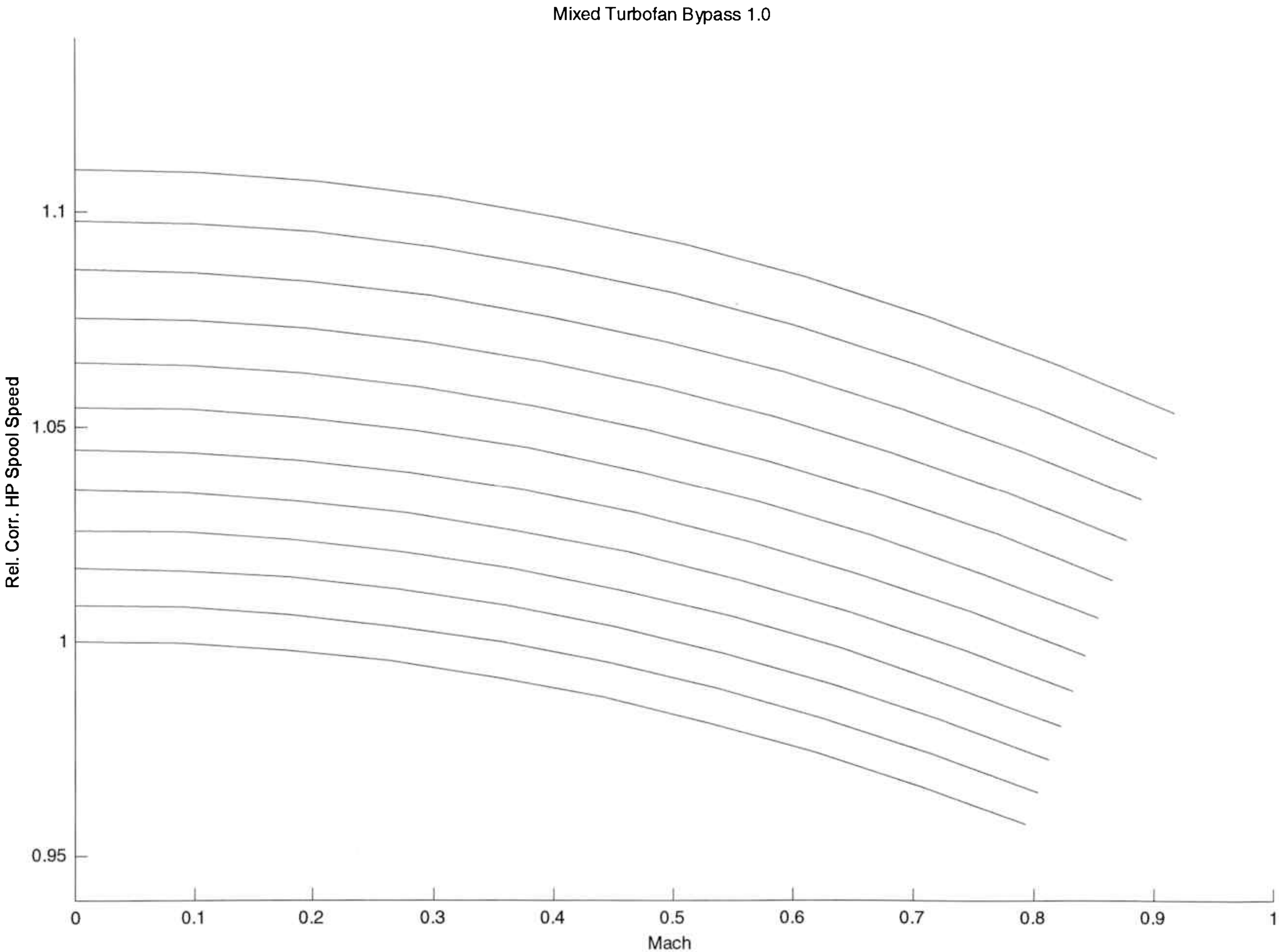


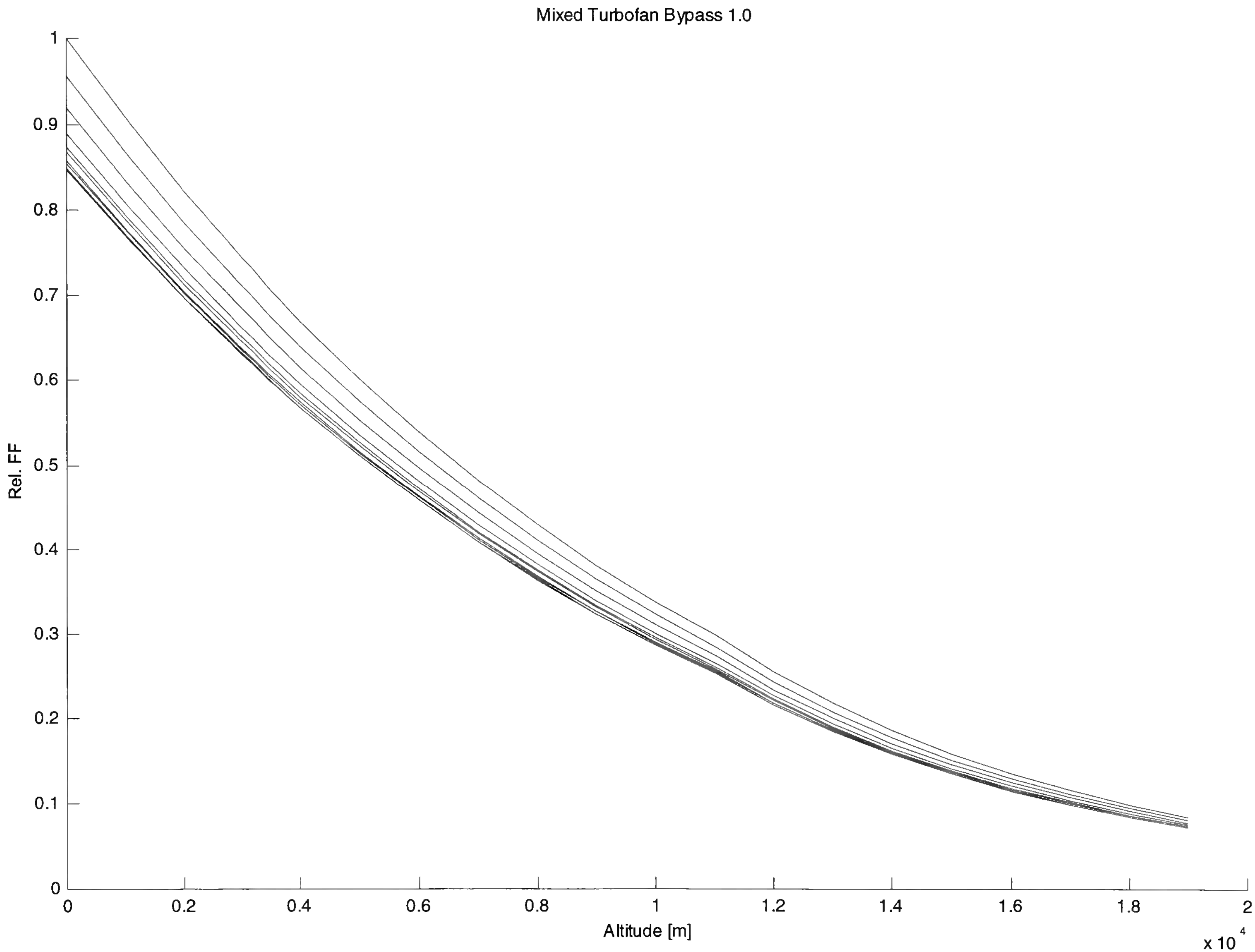
Mixed Turbofan Bypass 1.0
Rel. Corr. LP Spool Speed
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Altitude [m]
x 10^4


Mixed Turbofan Bypass 1.0
Rel. Corr. LP Spool Speed
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Mach

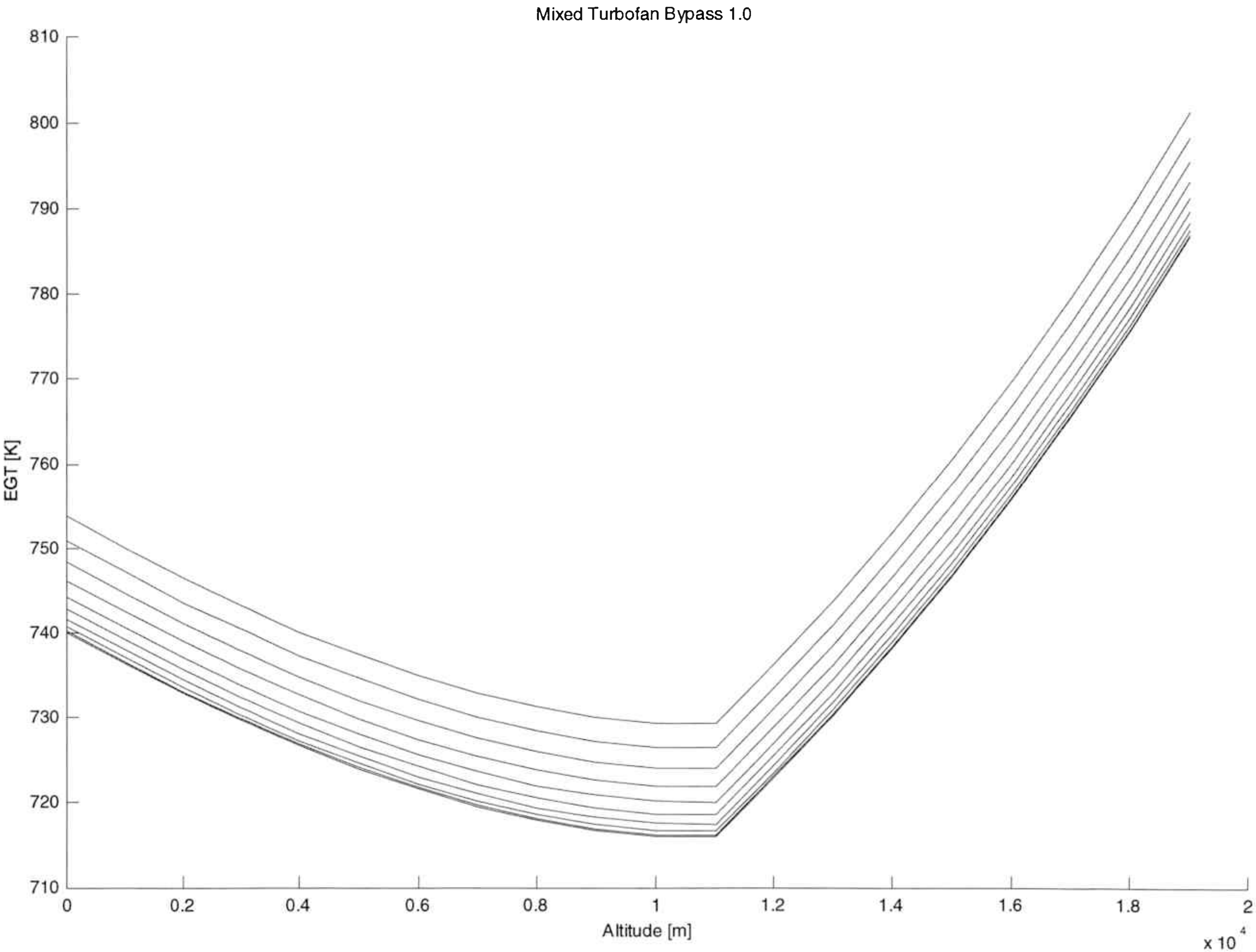


Mixed Turbofan Bypass 1.0
Rel. Corr. HP Spool Speed
1.1
1.05
1
0.95
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Altitude [m]
x 10^4


Mixed Turbofan Bypass 1.0
Rel. Corr. HP Spool Speed
1.1
1.05
1
0.95
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Mach



Mixed Turbofan Bypass 1.0
Rel. FF
Altitude [m]
x 10^4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Mixed Turbofan Bypass 1.0
810
800
790
780
770
760
750
740
730
720
710
EGT [K]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Altitude [m]
x 10^4