FAULT TOLERANT MULTIVARIABLE CONTROL OF A MILITARY TURBOFAN ENGINE

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Abstract: A fault tolerant multivariable control system for a military turbofan engine has been developed at Volvo Aero Corporation in cooperation with University of Trollhättan/Uddevalla. Nonlinear multivariable controllers designed as scheduled linear H_∞-controllers is used for engine control and the system is designed with multiple control modes to be able to get a more optimal control strategy. For the F404-RM12 engine multiple sensor faults can be tolerated with only minor control impact. Both analytical sensor redundancy and estimation of non-measurable engine parameters have been used to achieve this. The concept also adapts for engine-to-engine variations.

Keywords: Engine control, Multivariable control systems, Fault tolerance, Nonlinear control, Estimators, H-infinity control

1. INTRODUCTION

A fault tolerant multivariable control system for a military turbofan engine has been developed in cooperation between Volvo Aero Corporation, University of Trollhättan/Uddevalla and Chalmers University of Technology. The project has been part of the Swedish National Flight Research Programme, NFFP 3. The project has shown that modern control design techniques can be applied to jet engine control, and that implementation in computer based control systems of today, for example in the F404-RM12 FADEC unit, is possible. However, an actual hardware implementation has so far not been made. A control design method for sampled multivariable robust control laws of reduced order has been developed and applied within the project. This method is based on linear process models and design parameters defined in continuous time, which from an engineering point of view, makes very good sense. Estimators/observers have been used to investigate benefits and to evaluate control possibilities with the use of estimated parameters from both safety and performance perspectives. However, in some cases the estimator complexity has been too high for implementation in an actual engine controller. Evaluation of concept and simulations has been performed at Volvo Aero Corporation with a complete system model for the F404-RM12 engine, which is the engine used in the JAS39 Gripen aircraft. Both MATRIX_X and Matlab/Simulink have been used for design and simulations. The paper starts with a description of the RM12 engine, the one to be controlled, and the complete control system, with the different sub functions. After this, design aspects are considered with special emphasis on control mode switching and sensor fault tolerance. These two sections are followed with illustrating simulations and discussions of the results.

2. THE ENGINE CONTROL SYSTEM

The engine control system consists of different functions within two main feedback loops. One inner loop handles the actual engine control, and another

Table 1. Abbreviations

A8	Outlet nozzle throat area (pos. 8).
CVG	Compressor Variable Geometry, variable stator vanes
FADEC	Full Authority Digital Engine Control
FI	Flight Idle, a low thrust setting
FN	Net Thrust
FVG	Fan Variable Geometry, variable stator vanes
HWIL	Hardware in the loop
IRP	Intermediate Rating Power; max core power and no afterburner.
JAS	Intercept, Strike, Reconnaissance (translated from Swedish)
PT5	Total Pressure at turbine outlet (pos. 5), is used for control feedback.
NH	High-pressure spool speed, is used for control feedback.
NL	Low-pressure spool speed, is used for control feedback.
SLS	Sea Level Static, an engine operation condition.
T5	Total temperature at turbine outlet (pos. 5), is used for control feedback.
WFM	Main fuel flow

outer time-separated loop is used for system optimisation, see Fig. 1. The system is designed with multiple control modes in order to obtain a flexible control strategy. The choice of mode can be from a strategic point of view, or in the event of a system or sensor failure. For the F404-RM12 engine multiple sensor faults can be tolerated with only minor performance impact, and to achieve this both analytical sensor redundancy and estimation of non-measurable engine parameters have been used.

2.1 Plant Description

The Volvo Aero RM12 engine is a two-spool military turbofan engine in the GE-F404 family and is used in a single engine configuration in the Swedish multi-role fighter JAS39 Gripen. The engine has a one-channel FADEC with a hydro mechanical backup control system. A schematic picture of the engine with sensors and actuators is presented in Fig. 2 and in Table 1 the signals and engine abbreviations. The afterburner and the cooled radial flame holder are however excluded from this control system.

2.2 Control System Functional Overview

In this section the functions in Fig. 1 will be described in further detail with some important insights to engine control. The block "Control laws" work only with relative signals (scaled deviations from operating point), and at steady state the default state value of zero is never far from the correct value. This means that time for state initiation, even at an engine restart, will never be a problem. For each operating point there are actually four separate control laws, one for each of the four control modes, see section 2.3, which all can control the engine at any operating point. A limiter is introduced to take care of engine control and actuator limitations. The RM12 FADEC of today has a digital actuator loop closing, which enables the control system to adapt to real circumstances. For example, if an actuator gets

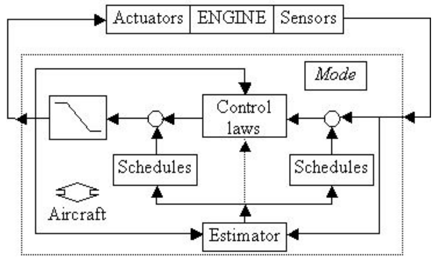

Fig. 1. A schematic drawing of the engine control function.

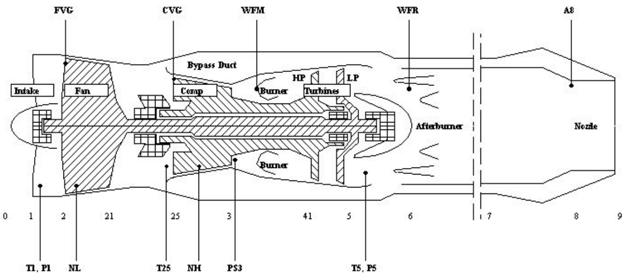

Fig. 2. The F404-RM12 engine with marked sensor and actuator signals.

stuck or is not able to move beyond a certain point, this information can be fed to the control limiter and the control anti windup will be able to handle this limitation. The control schedules consist of two main parts, the inlet signal schedules and the control signal schedules. These are functions of the actual state of the engine, the inlet or flight conditions and the pilot or thrust demand. An estimator is included in the system to be able to get reliable thrust estimation, used to optimise the engine operation and for analytical redundancy. The engine control system is also interacting with the flight control system and the aircraft and moreover equipped with a control mode decision logic. The two last functions will not be part of this paper.

2.3 The Main Control Modes

The control system is designed with four main control modes, see Table 2, and each of these modes can control the engine.

Table 2. The four different main control modes

	PT5	T5
NL	1	2
NH	3	4

The decision of these specific modes is based on experience, however methods to decide which structure a controller should have are presented in (Härefors 1999), and his studies point in the same direction as the one chosen. In (Härefors 1995) a switched MIMO(5,4) H_∞-controller is chosen for the RM12 engine, and promising results from this early study is the main reason why H_∞ is used here. Each of the four modes uses a set of two measurements and the main fuel flow, WFM, and the variable nozzle throat area, A8, for actuation. The variable fan and compressor geometry (FVG and CVG) are in this concept scheduled. Mode 1 uses NL and PT5, mode

2 NL and T5, etc, see Table 2. For control law design an H_∞-control design method based on the developments presented in (Christiansson 2003) is used. The resulting linear controllers are gain scheduled to handle the non-linear behaviour of the engine, such that one controller is active at all times. The controllers are designed to follow reference, integral action therefore included, and an anti-windup scheme is applied so that the inactive controller integral states do not windup. The controllers must also be able to handle mode switches and actuator restrictions. While inactivated each mode is positioned in its zero (optimal) setting and the controller states are used for matching of the active engine controller.

2.4 Sensor Fault Handling

Each of the four control modes (Table 2) can control the engine, and in the case of a sensor fault or complete failure, a mode switch can accommodate this situation when it occurs. Furthermore the most critical sensors are redundant, like NL, NH and TT5. However, undetected faults or failures is another matter and will still be a hazard for the system. Undetected, they still present problems, but not more so than in the current control system. In this concept the two modes, 1 and 3, use the PT5 sensor, which is not redundant, but has, on the other hand, proven to be reliable in practice. In this study a realistic sensor fault detection system is supposed to exist.

2.5 Engine-to-Engine Variations

Unfortunately each engine is an individual and all engines degrade while in use. This leads to a situation where control settings differ between engines and the response to a pilot command is situation and engine dependent. Furthermore, an engine, while in service, must live up to the specification, i.e. minimum thrust and transient times. This means that when new, the engine will perform better than the specification, and in time for service the requirements will just be fulfilled. Effects from engine-to-engine variations can with a reliable thrust estimation included be minimised. The control system could then adapt for these variations with less engine life consuming usage as one result, and with lower fuel consumption as another. In the following, section 4.3, this matching of thrust is illustrated with a thrust controller. Engine parameter adaptations may sound like a very big issue, but quite few parameters are needed for a fairly accurate onboard estimation. For the RM12 engine three to four parameters are enough, which can be concluded from engine trending. In (Grönstedt and Wallin 2004) a parameter estimation analysis for the RM12 is presented with a higher aim compared to what is needed for onboard parameter tracking. With all parameters with slow or known variations (time between overhauls) excluded, the number of parameters will be reduced, reduction is however not presented in the paper.

3. DESIGN CONSIDERATIONS

The controllers are scheduled linear control laws and the designs are based on generalised linear methods. In this section the design approach and a few insights will be shared, while simulation results are shown in the next section.

3.1 Control Design

In the control design, linear representations of the engine are used for the model based H_∞-design method. These linear models are generated with singular perturbation from a non-linear thermo-dynamical engine model in MATRIX_X SystemBuild with 34 dynamical states. This non-linear model is also used for concept evaluations and HWIL testing. In Fig. 3 the system singular values are presented for linear engine models covering the flight envelope. The singular values of the product of observability and controllability gramians, in Fig. 5, indicate that reduced order linear models with 9 states are suitable for control and 2 to 6 for estimation. A procedure for the reduction down to 9 states is presented in (Härefors 1995). The H_∞-control design method developed in (Christiansson 2003) is based on loop shaping, and the method uses design filters and a linear plant model defined in continuous time. Through lifting and optimisation the design method results in low order sampled state-space control laws. The full order controllers have 15 states and can be reduced to 4 with almost the same performance (Christiansson, *et al.* 2005). The basic design considerations and the linear engine model reduction approach are presented in (Härefors 1995). The design weights are chosen to be of diagonal PI-type with a constant gain below 1mHz. Sensors and actuators are represented by linear lowpass filters (4).

3.2 Control Scheduling

From the system singular values in Fig. 3 one can conclude that the engine model does not change that much in the flight envelope (uninstalled), and even better model agreement is achieved after operating point input, output and state normalisation. With a fixed A8 as for commercial engines the difference is even less. In (Härefors 1995) switching between controllers is used, but in this case input-output normalisations have shown to be good enough. As a result a normalised state space A matrix for the controller at the IRP operating point is used with input and output scheduling, see equation (1).

$$\begin{cases} x(k+1) = Ax(k) + BT_U u(k) \\ y(k) = T_Y^{-1}Cx(k) + T_Y^{-1}DT_U u(k) \end{cases} \tag{1}$$
$$T_U = T_U(\rho), \quad T_Y = T_Y(\rho)$$

The scheduling parameter, ρ, is a function of ambient conditions and engine operating point. T_U and T_Y are diagonal 2-by-2-matrices. Full parameterisations have been tested with only slightly better performance. The scheduled T matrices have been calculated by matching the controller from a chosen operating point with the other operating point controllers in the system singular value domain. Note that the controllers always run with normalized inputs and outputs. Equation (1) is also presented as a part of the flow in Fig. 5.

3.3 Control Mode Switching and Anti-Windup

The control laws have integral action for reference tracking without steady-state errors and the integrator windup must be handled. The total number of states in the control system has been a restrictive factor and an anti-windup with as few states as possible is therefore preferable. From extensive simulations the use of the linear engine model DC-gain (P_{DC} in Fig. 5) as anti-windup feedback have proven to be a reliable solution; the same linear model that was used for control design. Due to the choice of controller scheduling one anti-windup gain for each control mode is enough. The data needed is even less taking into account the fact that each mode shares one input with another mode. The scheme is shown in Fig. 5. While inactive the controller input is set to zero. This is a slight simplification, but due to the fact that the controller D matrix elements are comparably small the effect will therefore be neglectable. This method will however not lead to a bumpless transfer because the input schedules will not match the engine completely, and switching from one mode to the other will have a small but noticeable effect on the control signals, se section 4.2. If the method had been applied to modes using the same set of inputs this would have worked as a bumpless transfer, similar to the conditioning technique in (Rönnbäck 1993). The controller must be able to handle the case of actuator or operational constraints in a general manner. For example, if one of the control signals is limited the anti-windup feedback will for that signal deviate from zero and result in a new feedback structure. The anti-windup feedback will therefore effect the whole controller and for a non-diagonal MIMO controller all the control signals will be effected if just one gets limited. This is something ignored in most SISO designs, but for a MIMO controller with integral action, this will effect the balance between the control signals.

3.4 Engine Estimator

The engine estimator consists of a non-linear engine model resembling the one used as the engine. The estimator is designed with a time constraint on state error convergence using a linear Kalman filter approach (Glad *et al.* 2000; Ring 2000). One set of filter parameters has shown to work satisfactory for the total operating region. The linear predictor is therefore replaced with the non-linear model. A

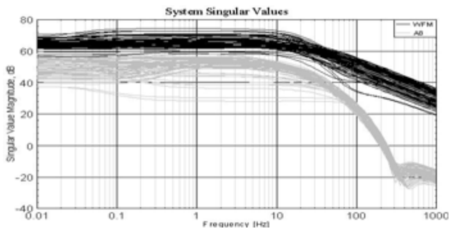

Fig. 3. System singular values for 93 operating points throughout the flight envelope (not installed engine). WFM (black) and A8 (grey), with NL, NH, T5 and PT5 as outputs.

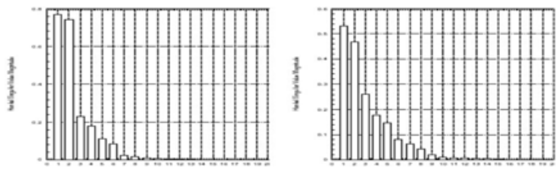

Fig. 4. Hankel singular values at IRP SLS. To the left for thrust estimation and to the right for control.

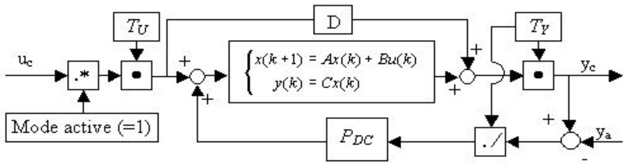

Fig. 5. Controller with input-output scheduling and anti-windup.

straight forward method that has proven to be useful. Integral action is included for the very reliable spool speed measurements, NL and NH, which also are the two most dominating states from a thrust estimation point of view, se Fig. 4. The estimator handles sensor failures by removing the sensor inputs. A loss of two sensor signals is managed as long as at least one of the two spool speeds is available. There are two reasons for the integral action on the spool speeds. First, the nonlinear model has to be remodelled to allow for direct state inputs, which was not reasonable, and a good matching of the spool speeds is very important for acceptable estimator performance. Secondly, when using a filter one can design for disturbance rejection, which is desirable, and furthermore the sensor signal could be excluded. Unfortunately the estimator is heavily dependent on reliable control input, which also is true for correct ambient condition. A similar observer was developed by (Ring 2000) in the BE97-4077 OBIDICOTE.

4. SIMULATION RESULTS

Evaluations of the developed control system have been performed with access to all Volvo Aero system models, which also are used for engine performance analysis and these models are proven to be very authentic. The used non-linear models are $MATRIX_X$ SystemBuild models with external C and FORTRAN code.

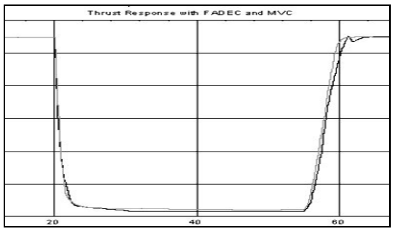

Fig. 6. A step from IRP to FI and back to IRP at SLS with FADEC (black) and with mode 1 (gray).

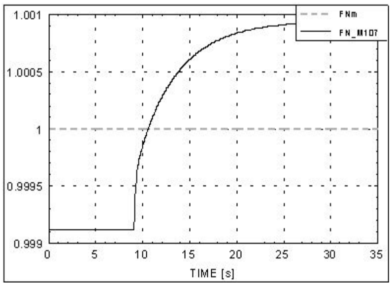

Fig. 7. Thrust during a change from mode 1 to 3. Note that the relative deviation at IRP is within point one percent of the demand (=1).

4.1 Transient Behaviour

In the current FADEC there exist multiple controllers like the part power, maximum power, acceleration and the deceleration controller, plus limiting controllers. Fig. 6 shows a step response for both FADEC and the presented control system when a step from IRP to FI and back to IRP is carried out. The FADEC system goes from max power via deceleration to the part power via acceleration back to the max power controller and the developed system, the grey plot, just uses the MIMO mode 1 controller. The proposed design is thus simpler and performs even better (in this specific example).

4.2 Mode Switching

The control system is designed with four control modes (Table 2). In Fig. 8 to 10 the thrust response, the measurement errors, and the control signal are presented while a switch from mode 1 to mode 3 occurs. A switching of mode is to go from one set of measurements and one controller to another combination. The control schedules generate reference values from pilot demand, state of the engine, and ambient conditions, see Fig. 1. These references give the desired setpoint. However, the engine uniqueness will result in the need for individually tuned schedules, which do not exist and a switch will therefore not be bumpless. The effect is damped by the anti-windup, section 3.2. Looking at Fig. 8 one can see how the integral actions in the controllers achieve the measurements at their setpoint, i.e. in mode 1 PT5 and NL and in mode 3 PT5 and NH. Note how the new mode leads to a different NL. The thrust in Fig. 7 follows the controls in Fig. 9. The changes in Fig. 8 to 10 are relative and realistic and please note that the relative measurement errors are within 0.15%, the thrust

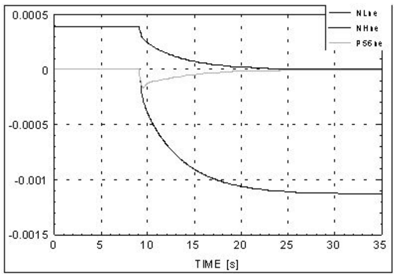

Fig. 8. NL, NH and PT5 (grey) error during a change from mode 1 to 3. NL and PT5 are zero at the beginning and NH and PT5 zero at the end.

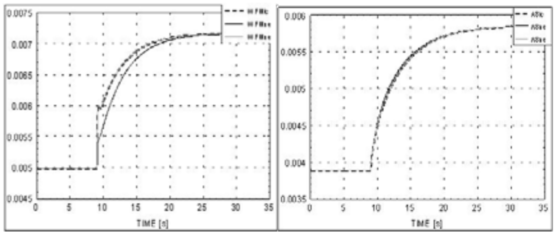

Fig. 9. Controller WFM (left) and A8 (right) at mode change from mode 1 to 3. The control signal is the dashed line.

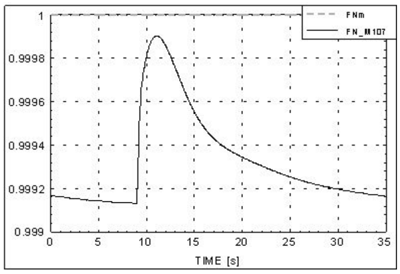

Fig. 10. Thrust during a change from mode 1 to 3 with thrust control applied. Compare with Fig. 7 and note how small the total effect is at IRP.

0.1% and the controls 0.3%, all very small changes. Similar results are obtained when switching between different modes.

4.3 Thrust Control

The estimator in Fig. 1 can be used for thrust estimation and the given thrust command could therefore be matched with the estimated thrust. In Fig. 7 the actual thrust is displayed during a mode change, from 1 to 3, and compared to Fig. 10 it is obvious that one gets the same steady-state thrust before and after. With an estimator that could adapt to individual engines and to engine degradation the thrust control could be used to always get the same response independent of the engine. Thrust control is therefore a powerful way to adapt to engine-to-engine variations.

3.4 Sensor Fault Handling

Most of the important sensors in the RM12 engine are redundant; apart from this, one could instead use analytical redundancy to handle senor faults. In Fig. 11 the measured NL is replaced by an estimate and this estimate is used for feedback control, which means that the estimator becomes part of the feedback loop. This is in general not a perfect situation, because the real engine response will be filtered through the estimator. However, it will work here due to the nice properties of the engine, and it is actually in this case avoidable. A better approach for this actual fault would be to switch from mode 1 to mode 3, see Fig. 7 to 9, and exclude NL from the control feedback loop. The most troublesome sensor faults are in the actuator feedback and the inlet condition sensors, which will effect the whole engine system, but this is an existing problem and handled in the state-of-the-art control systems of today.

5. IMPLEMENTATION ASPECTS

The RM12 FADEC can, when it comes to calculation capacity, be compared to a Macintosh from the early 1990s. The capacity is therefore quite limited and the proposed control system with included estimator will not be implementable. However, the control system with a simpler estimator may very well be possible. Furthermore, the presented estimator provides far more usage and opportunities compared to what is needed for control. The state-space representation of the control laws, and the number of states compared to the current state-of-the-art controllers will not be more of a problem than for any other MIMO controller, which has in brief been discussed in this paper, the fragility problem and the matrix calculations must naturally be handled.

6. SUMMARY

A full multivariable robust computer based control system concept for a military turbofan engine control system has been described. The concept includes fault handling and nonlinear issues. Comparisons are also made with the state-of-the-art solution. In Fig. 6 one can clearly see that a multivariable controller can be used to control a turbofan engine of the GE-F404 family with a much easier-to-follow function. The paper has also illustrated the use of engine estimators for control and shown the advantages, but also pointed out some limitations. The possibility to handle feedback loop senor failures, either through the use of estimated signals or through mode switching, is exemplified.

Table 3. Continuous Engine System Matrix at SLS

-134	-134	5.14	4.97	-0.07	50.7	50.7	-86.5	135	0	0
-21.1	-144	0.36	0.3	-0.03	18.4	18.4	-34.1	78.6	0	0
166	166	-209	-122	5.61	2.55	2.55	247	-43.5	0	0
-67.6	-67.6	-1.19	-179	99.7	-0.93	-0.93	-77.9	28.9	0	0
0	0	0	0	-100	0	0	0	0	100	0
80.4	80.5	65.2	36	0.22	-156	-110	4.66	-18.5	0	-94.3
-31.2	-31.2	13.2	95.4	3.11	21.2	-91.9	0.97	8.73	0	-19
-1.21	-1.21	1.5	2.37	0.01	-0.07	-0.07	-3.83	0.17	0	0
-0.89	-0.89	3.03	3.56	0.04	-1.63	-1.63	0.17	-2.61	0	0
-0.04	-0.04	-0.06	0.82	0.02	0.18	0.18	0	0	0	0
0.03	0.03	0.03	0.03	0	0.94	0.94	0	-0.01	0	0
0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	1	0	0	0

8. MODELS

A reduced linear continuous engine model with limited precision is presented in Table 3 as a system matrix [*A,B;C,D*], [WFM;A8] to [T5;PT5;NL;NH]. The engine model used for simulations and evaluations is a complete nonlinear transient thermo dynamical turbofan model with 34 dynamical states (2). The structure of the estimator is presented in (3). N denotes spool speeds and * the other 32 states. Sensors T5 and PT5 are similar to the nozzle filters (4), NL and NH are much faster and dynamics omitted.

$$\begin{cases} \dot{x} = f(x,z,u) \\ 0 = g(x,z,u) \\ y = h(x,y,z) \end{cases} \quad y = \begin{bmatrix} y_x \\ y_m \\ y_e \end{bmatrix} \quad u = \begin{bmatrix} u_c \\ v \end{bmatrix} \tag{2}$$

$$\begin{cases} \dfrac{d\hat{x}_N}{dt} = f_N(\hat{x},\hat{z},u) + L_N(y-\hat{y}) + x_i \\ \dfrac{d\hat{x}_\bullet}{dt} = f_\bullet(\hat{x},\hat{z},u) + L_\bullet(y-\hat{y}) \\ \dfrac{dx_i}{dt} = k_N(y-\hat{y}) \\ 0 = g(\hat{x},\hat{z},u) \\ \begin{bmatrix} \hat{y} \\ \hat{x} \end{bmatrix} = \begin{bmatrix} h(\hat{x},\hat{z},u) \\ \hat{x} \end{bmatrix} \end{cases} \quad \hat{x} = \begin{bmatrix} \hat{x}_N \\ \hat{x}_\bullet \end{bmatrix} \tag{3}$$

$$\underline{\text{Fuel flow actuation:}} \quad \frac{1}{0.025s+1} \qquad \underline{\text{Nozzle actuator:}} \quad \frac{1}{0.05s+1} \tag{4}$$

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