Timescaling Control Volumes During Real Time Digital Simulation of a Military Turbofan

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Nomenclature

A_{nz}	=	exhaust nozzle area
D_T	=	frame time
dt	=	change in time
N	=	spool rotational speed
P	=	total pressure
Q_{HPT}	=	high-pressure turbine (HPT) flow capacity
Q_{LPT}	=	low-pressure turbine (LPT) flow capacity
R	=	gas constant
T	=	total temperature
t	=	time
U_W	=	upstream mass flow
Vol	=	control volume
W	=	mass flow rate
W_F	=	main combustor fuel flow
$\boldsymbol{X}$	=	state vector
γ	=	ratio of specific heats
ΔW	=	mass flow accumulation

Subscripts

H	=	high pressure spool
L	=	low-pressure spool
2	=	fan [low-pressure (LP) compressor] exit
3	=	high-pressure (HP) compressor exit/combustor entry
5	=	HP turbine exit/LP turbine entry
6	=	LP turbine exit

Introduction

THE real-time digital simulation of the dynamic response of an aircraft gas turbine engine is achieved when the cycle time, that is, computation time for one pass through the engine dynamic model, is shorter than the integration time-step size (or frame time D_T). The engine considered is a twin-spool, military turbofan with mixed exhausts. An explicitly time-integrated, real-time aerothermodynamic model of this engine based on state variables and control volumes is described in Ref. 1. The inputs to the model are flight conditions and control parameters, that is, main combustor fuel flow W_F, reheat fuel flow, compressor variable geometry (VG) setting, and exhaust nozzle area A_{nz}. The state vector $\boldsymbol{X}$ includes six parameters, $\boldsymbol{X} = (P_2, P_3, P_5, P_6, N_L, \text{and } N_H)$; hence the model is referred as six state variables (6-SV) model. A typical engine schematic is shown in Fig. 1 of Ref. 1.

At the prescribed flight condition, the components' operation is found using the control inputs and initial state vector. The torque difference between the compressor and turbine on the same spool is used to generate the time derivative of rotational speed. The mass flow accumulation in a control volume ΔW is used to calculate the time rate of pressure change, that is, $dP/dt = (\gamma RT/\text{Vol}) \cdot \Delta W$. The next engine state is computed using an explicit integration scheme, $\boldsymbol{X}(t + D_T) = \boldsymbol{X}(t) + D_T \times \boldsymbol{G}(\boldsymbol{X}, \boldsymbol{U}, t)$, where $\boldsymbol{G}$ is differential equations vector and $\boldsymbol{U}$ is input vector.

A total of four control volumes, that is, Vol2, Vol3, Vol5, and Vol6, are defined to update the state variables P_2, P_3, P_5, and P_6, respectively. Vol2 is the summation of the volumes of the low-pressure compressor, intercasing duct, and the bypass duct; Vol3 is the volume between high-pressure compressor and high-pressure turbine (HPT); Vol5 is the volume between HPT and low-pressure turbine (LPT); and Vol6 is the entire jet-pipe volume from the LPT exit to the exhaust nozzle. Vol6 is the largest, and Vol2, Vol3, and Vol5 are about 0.50, 0.17, and 0.03 times Vol6, respectively.

The pressure dynamics, being faster than rotor dynamics, restricts the size of usable D_T. A small D_T is required to track pressure dynamics accurately, while updating the engine state, thereby making it difficult to simulate engine transients in real time on a digital computer. A standard practice to increase D_T is to artificially dampen the pressure dynamics by choosing large control volumes. It permits a larger D_T, generally in the same proportion as the increase in control volume sizes with respect to their actual physical values, while retaining the accuracy and stability of analysis. This procedure, termed timescaling of control volumes, does not significantly affect the overall transient behavior because it is determined by the rotor dynamics due to its long time constant.

However, there is no mention of whether this timescaling should be done uniformly on all of the control volumes or only on a particular one. But, during the course of numerical studies using the 6-SV model, it was observed that it is sufficient to timescale the smallest control volume, that is, Vol5, to increase the D_T. This Note first provides justification as to why there exists an upper limit on usable D_T when actual control volumes are used and then explains the reasons for timescaling only the smallest control volume.

6-SV Real-Time Model

The 6-SV model[1] used in this work is basically the modified version of a baseline 9-SV model.[2] A brief overview of the baseline 9-SV model, the reasons why D_T is limited to 0.10 ms in the baseline model (thereby preventing its real-time simulation), and how this limitation is overcome by modifying it to the 6-SV model are contained in Ref. 1. Reference 1 also includes the validation of the 6-SV model. For a prescribed time change in W_F and A_{nz} (open-loop simulation) and with actual control volumes, the 6-SV model permits a D_T of 0.30 ms with good accuracy and D_T of 0.40 ms at reduced accuracy, with respect to the baseline response. It was further shown that by timescaling the control volumes up to five times, D_T of 2.0 ms could be used, although accuracy decreases with increase in timescaling. Because cycle time is approximately equal to 0.70 ms on a DOS-based Pentium-III machine, a $D_T \geq 1.0$ ms is adequate for its real-time execution because it also leaves sufficient allowance for data communication during hardware-in-loop simulation. The 6-SV model described in Ref. 1 is based on the assumption that static pressure is uniform across the mixer. However, a static pressure rise of 2% across the mixer was incorporated (from the experience of 9-SV model) during the course of present work, to improve its accuracy.

At the time of reporting the results contained in Ref. 1 for the 6-SV model, a uniform timescaling was done on all of the control volumes. Subsequent to that, it was observed that it is only the smallest control volume, that is, Vol5, that needs to be scaled, not all of the control volumes. This also aids to improve the model numerical accuracy. It was this observation that led to further investigations in trying to understand the sensitivity of a timescaling scheme on the numerical accuracy and the stability of a transient simulation.

Control Volumes Timescaling

The baseline transient for the studies contained in this section is a 1.5-s ramp change in control variables (W_F and A_{nz}, at a prescribed VG schedule) that corresponds to engine excursion from idling to

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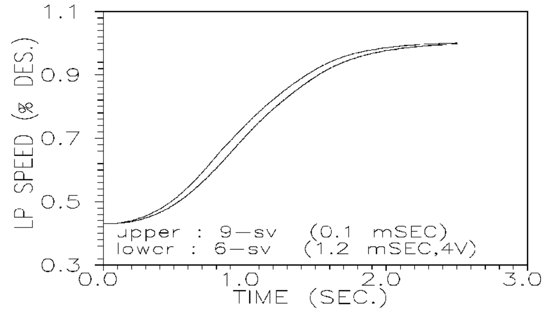

Fig. 1 N_L response with different timescaling schemes.

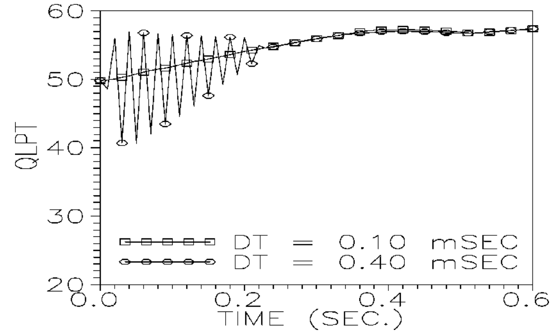

Fig. 2 Influence of D_T on Q_{LPT}.

maximum speed at sea level static (SLS) in international standard atmosphere (ISA). The 1.5-s ramp was chosen because it is typical of the least time taken by the controller hardware to effect desired change in control inputs. Because of the nonavailability of actual engine response from test results, the simulated response from the baseline 9-SV model for this transient forms the baseline validation data.

The 6-SV model was run at D_T of 1.20 ms, first with uniform timescaling of four times on all the control volumes and then by scaling only Vol5 by four times. The resulting N_L response for the baseline case on uniform timescaling of control volumes is shown in Fig. 1. The response obtained by timescaling Vol5 alone is nearly the same as the baseline and, hence, is not shown in Fig. 1 to retain its clarity. It can be seen from Fig. 1 that N_L response with uniform timescaling (the lower curve) deviates from the baseline. A similar trend was observed for other parameters. Only the first 2.50 s of the transient are shown in Fig. 1 because this is the period during which the effects of pressure dynamics and, hence, the deviation are noticeable. Thus, timescaling only Vol5 produces a more accurate simulation at a higher D_T and only for that portion of transient during which the pressure dynamics is significant.

Before determining why timescaling of Vol5 alone results in a more accurate simulation at higher D_T, it is necessary to understand why there exists an upper limit on D_T when actual control volumes are used. For this purpose, a brief description of the influence of P_5 is presented. P_5 controls the pressure ratios of the HPT as well as the LPT. The turbine maps are searched using the corrected speed and pressure ratio as the inputs, and the output parameters are the flow and work capacity. The HPT gets choked at a lower speed in comparison to LPT, and in an engine excursion from idling to maximum speed, HPT is usually choked at the idling speed itself. Thus, any variation in P_5 will not significantly affect the HPT performance, but it does influence the LPT until it also gets choked. To summarize, in the initial phase of a large transient from idling to maximum speed, LPT will be sensitive to the variations in P_5 until it gets choked.

The mass flow accumulation in Vol5 ($U_{W_5} - W_5$) is used to compute $\mathrm{d}P_5/\mathrm{d}t$. Whereas U_{W_5} is the incoming mass flow based on upstream HPT characteristics, W_5 is computed using the LPT flow capacity Q_{LPT}, which is the mass flow that can pass through the LPT. Consider the situation where D_T is increased to 0.40 ms at actual control volumes. With increasing D_T, the updated P_5 for the next engine pass also increases. As a result, the pressure ratio of HPT decreases and that of LPT increases (turbine pressure ratio is equal to entry P/exit P). Because HPT is choked, it does not affect the HPT flow capacity Q_{HPT} and, hence, U_{W_5}, but T_5 increases because the temperature drop is lower due to a lower HPT pressure ratio. An increased LPT pressure ratio while it is still not choked increases Q_{LPT}. An increase in Q_{LPT}, P_5, and T_5 simultaneously leads to an increase in W_5 because it is computed as $Q_{\mathrm{LPT}} \times P_5/\sqrt{T_5}$. Because W_5 increases, the net resultant of $U_{W_5} - W_5$ reduces, causing a decrease in P_5 for the next engine pass. The lower P_5 results in a reverse situation, causing P_5 to increase for the following engine pass. This cyclic variation in P_5 continues until LPT also begins to get choked and $\mathrm{d}P_5/\mathrm{d}t$ begins to reduce in magnitude.

The influence of cyclic variations in P_5 also gets propagated in the parameters that are used to compute $\mathrm{d}P_2/\mathrm{d}t$ and $\mathrm{d}P_6/\mathrm{d}t$. Because Vol2 and Vol6 are large, variations in $\mathrm{d}P_2/\mathrm{d}t$ and $\mathrm{d}P_6/\mathrm{d}t$ are not as pronounced as $\mathrm{d}P_5/\mathrm{d}t$, but it does affect the engine dynamics. The $\mathrm{d}P_3/\mathrm{d}t$ is relatively shielded from the P_5 effect because of the choked HPT and because, at speeds from idling and above, the HPC flow function (and, hence, its mass flow) is not very sensitive to the variations in its pressure ratio. The variations in the HPT and LPT pressure ratios further influence the spool torque imbalance, thereby affecting $\mathrm{d}N_L/\mathrm{d}t$ and $\mathrm{d}N_H/\mathrm{d}t$. As a result, engine speed response deviates from the baseline when D_T of 0.40 ms is used with actual control volumes.

To summarize, with actual control volumes, there is a limiting D_T, after which the P_5 dynamics becomes unstable, thereby affecting the overall engine response during the initial phase of a large transient. The time variation of Q_{LPT} (where W is in pounds per second, T is in Kelvin, and P is in psia pounds per square inch absolute) at two values of D_T, that is, 0.10 and 0.40 ms is shown in Fig. 2. It can be seen that Q_{LPT} builds up steadily to its choking value at the lower D_T. However, at higher D_T, there is a cyclic variation in Q_{LPT} during the initial phase. It oscillates (increases and decreases) around the Q_{LPT} obtained at D_T of 0.10 ms. This variation gradually reduces, and finally Q_{LPT} takes its choking value.

To isolate the influence of LPT not choked, another transient was carried out at ISA, SLS in which a 1.5-s ramp in control inputs caused N_L to change from 90 to 100% (of its design value). The HPT and LPT were both choked in this regime. It was observed that cyclic variations in P_5 still take place, although at a much higher D_T of 0.80 ms. Because LPT is choked, cyclic variations in P_5 in this case are attributed to a small Vol5. Thus, Vol5 does play a significant role in limiting the usable D_T for an accurate tracking of P_5 dynamics. A choked LPT does not eliminate P_5 oscillations and only increase the D_T at which they occur.

The foregoing description makes it clear that any further increase in the size of usable D_T will require an artificial increase in Vol5. What needs to be ascertained is whether such an increase is required for other volumes as well. For this purpose, analysis was performed with two timescaling schemes: 1) done uniformly on all of the volumes and 2) done only on Vol5. It was observed that when a timescaling of four times was applied uniformly on all of the volumes or only on Vol5 a D_T of 1.20 ms could be achieved, with a smooth variation in LPT parameters. Any higher D_T or a lower timescaling results in P_5 oscillations, which is not acceptable.

However, as evident from Fig. 1, N_L response deviates from the baseline when all of the control volumes are uniformly timescaled. The reason is that timescaling of large control volumes reduces the rate at which the pressures associated with them are updated. The numerator of the equation $\mathrm{d}P/\mathrm{d}t = \gamma RT/\mathrm{Vol} \cdot \Delta W$ does not increase in the same proportion in which the volumes are increased. As a result, the rates of pressure buildup are slower. It also reduces the spool torque imbalance, due to which the N_L response, as shown in Fig. 1, is always lower with respect to the baseline.

As a typical example, time variation of $\mathrm{d}P_2/\mathrm{d}t$ at $D_T = 1.2$ ms with a uniform timescaling of four times on all of the control volumes is compared with the baseline $\mathrm{d}P_2/\mathrm{d}t$ in Fig. 3. The timescaled $\mathrm{d}P_2/\mathrm{d}t$ lags behind the baseline until it attains a certain maximum value, after which it leads the baseline. This is due to the presence of large control volumes when all of the control volumes are uniformly

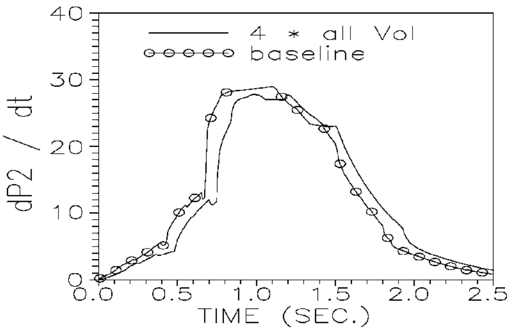

Fig. 3 Influence of uniform timescaling.

timescaled. However, the endpoints of P_2 dynamics are the same at the end of 2.5 s. Thus, the engine takes the same final steady state. A similar trend was observed for the time derivatives of other pressure terms as well.

Alternatively, timescaling only Vol5 by four times enables one to overcome this situation. In the 6-SV model, the maximum D_T that produces a numerically accurate and stable transient simulation at actual control volumes is 0.30 ms. It will be referred as case A. The present case, where Vol5 alone is scaled by four times to give a $D_T = 1.2$ ms, is case B. It was observed that at any instant of time during a transient, the numerical value of the term ΔW in the equation that computes dP_5/dt is greater by about four times in case B in comparison to case A. As a result, the time variation of dP_5/dt (and, hence, P_5) in case B is practically the same as in case A. This is because the increase in ΔW is compensated by an increased Vol5, thereby indicating that scaling Vol5 alone makes the P_5 dynamics stable, by eliminating (or reducing) its cyclic variations. At the same time, scaling Vol5 alone does not affect the dynamics of other pressure terms in the state vector. Also, the dynamics of pressure terms other than P_5 have larger time constants (with respect to P_5 dynamics) due to large volumes. Hence, an increase in D_T without scaling their respective volumes does not introduce any noticeable error in their update. Therefore, response prediction is in good agreement with the baseline.

An attempt is made to explain the aforesaid observation of the parameter ΔW, which is computed as $U_{W_5} - W_5$. Whereas U_{W_5} comes from the upstream HPT, W_5 is computed as $Q_{\mathrm{LPT}} \times P_5/$ *SQRT* (T_5). In an explicitly integrated transient simulation, the flow accumulation in control volumes and the spool torque imbalances at $t = n \times D_T$ are used to update engine state from $t = n \times D_T$ to $t = (n+1) \times D_T$. In addition, for every update in case B, case A needs to be updated four times (0.3 ms $\times 4 = 1.2$ ms) to reach the same level of time as in case B. Let 1.2 ms be the reference D_T, and consider the situation when engine state is updated from $t = 0$ to 1.2 ms.

In case A, the time derivatives of state-variables based on the engine state at $t = 0.90$ ms are used to determine the engine state at $t = 1.2$ ms. Case A would have already undergone three updates by the time it reaches $t = 0.90$ ms, that is, at $t = 0, 0.30,$ and 0.60 ms. As a result, there will be an increase in the values of T_5, P_5, and Q_{LPT} (if LPT is not operating choked), with respect to their values at $t = 0$.

Now consider case B. During the computation of W_5, the values of T_5, P_5, and Q_{LPT} at $t = 0$ are used, which are lower than their respective values at $t = 0.90$ ms (as in case A). As a result, the computed W_5 will be lower. Although T_5 comes in the denominator, it is present as a square root effect, which reduces its influence. When LPT gets choked, there will no significant variation in its value; nevertheless, due to a lower P_5, the W_5 will be lower. Because HPT operates choked, the upstream U_{W_5} is nearly constant during a time interval of 1.2 ms. Thus, the combined effect of a nearly constant U_{W_5} and a reduced W_5 increases the mass flow accumulation in Vol5, when a higher D_T is used on timescaling only Vol5.

In summary, because of a small Vol5, the time derivative of P_5 dictates the size of D_T. Therefore, if the dynamics of P_5 alone can be stabilized without affecting the dynamics of other pressure terms in the state vector, it is sufficient to produce a simulation that is numerically accurate and stable at higher D_T. With this consideration, timescaling of Vol5 alone is sufficient. However, note that the scaling required to achieve a certain D_T may not always be the same as stated in this Note. It will vary from engine to engine, depending on the actual physical dimensions of an engine.

Conclusions

The smallest volume in a twin-spool, mixed-flow military turbofan is between the HPT and LPT (Vol5) and is used to update P_5. P_5, therefore, has the highest frequency dynamics, and as such, use of a large D_T causes a cyclic variation in its update. This cyclic variation is more pronounced when LPT is not choked and, therefore, occurs at a much lower D_T. Because of the presence of cyclic variations in P_5, the response prediction deviates from the baseline. Thus, a small Vol5 limits the size of D_T during dynamic response studies using an explicitly integrated aerothermal model based on control volumes. For the 6-SV model described, a D_T of only 0.30 ms could be used to produce a numerically accurate and stable simulation.

The timescaling of control volumes is a standard practice to increase D_T to achieve real-time simulation. It was observed that instead of timescaling all of the control volumes by a predetermined factor, it is sufficient to timescale only the smallest one, that is, Vol5. It is because timescaling of volumes that are already large, for example, Vol2, Vol3, and Vol6, considerably dampens the pressure dynamics associated with them, which causes a deviation in the response. Alternatively, if only Vol5 is timescaled, it helps to do away with the cyclic variations in P_5, without affecting the dynamics of other pressure terms in the state vector. This not only makes the simulation stable, but also more accurate. It the present studies, timescaling only Vol5 by four times resulted in a D_T of 1.2 ms, with extremely good matching with the baseline response. Because the cycle time is approximately equal to 0.70 ms on a Pentium III, D_T of 1.2 ms produces a real-time simulation.

The foregoing conclusions are based on a reference transient in which a 1.5-s ramp in W_F and A_{nz} at a prescribed VG schedule caused an engine excursion from idling to maximum speed at SLS in ISA. However, these observations also repeated consistently for a number of idling to maximum speed transients at other flight points as well, thereby confirming that timescaling only the smallest control volume is sufficient. The actual magnitude of timescaling to achieve a certain D_T may differ from engine to engine and may not be unique.

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