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The Possibility of Instability in NGATS Upstream Control of Flow into Airports

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Representation, estimation and optimization of airport capacity has sought to establish constraints on the Pareto constraint curve for various combinations of arrival and departure for various time intervals as a function of factors such as weather, runway configuration, etc. The NGATS Concept of Operations 0.2 report poses the following research issue: "With trajectories manipulated 20 minutes or less ahead, how is trajectory stability affected? What is the effect on keeping computed-times-of-arrival (CTAs) and what is the effect on system functions that rely on CTAs?" Measuring aircraft flow upstream to control flow downstream can pose a time delay in the control loop (20 minutes with no prediction, but delay also occurs with prediction as any prediction error amounts to time delay). Such delay can cause flow instability if continuous control is implemented. MatLab Simulink® tools are employed to demonstrate the effect.

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1 yard (yd)	= 0.9 meter (m)	1 meter (m)	= 3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
		1 kilometer (km)	= 0.6 mile (mi)
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1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
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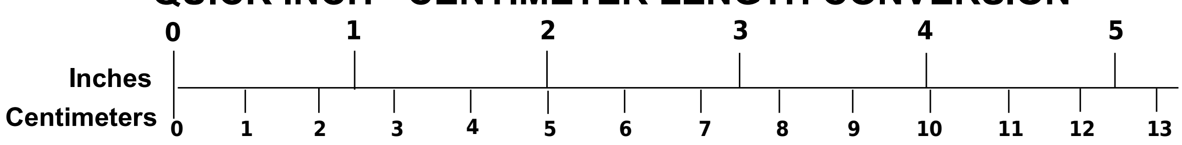

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°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
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Background

Representation, estimation and optimization of airport capacity has been a subject of research since the 1950s [1,2]. Typically the concern has been to establish constraints on the Pareto curve for various combinations of arrival and departure for various time intervals as a function of factors such as weather, runway configuration, etc. Upstream flow control of aircraft into airports (e.g. relative to an arrival fix) has been performed by human air traffic controllers, more recently aided by such tools as the Center-Terminal Radar Approach Control Automation System (CTAS) to assist in predicting near-future 4D trajectories.

The Next Generation Air Transportation System (NGATS) Concept of Operations [3] mentions that tactical trajectory management “is aided by automation that optimizes for a number of factors” (including weather, airport configuration, airline priorities, etc.) In this regard it poses the following research issue: “With trajectories manipulated 20 minutes or less ahead, how is trajectory stability affected? What is the effect on keeping computed-times-of-arrival (CTAs) and what is the effect on system functions that rely on CTAs?”

A Simple Dynamic Model

It would appear that the 20 minutes upstream control can mean a time delay in the control loop, and that to analyze the flow control between the terminal area airspace sector and the airport surface one can employ a simple linear dynamic model as shown in Figure 1.

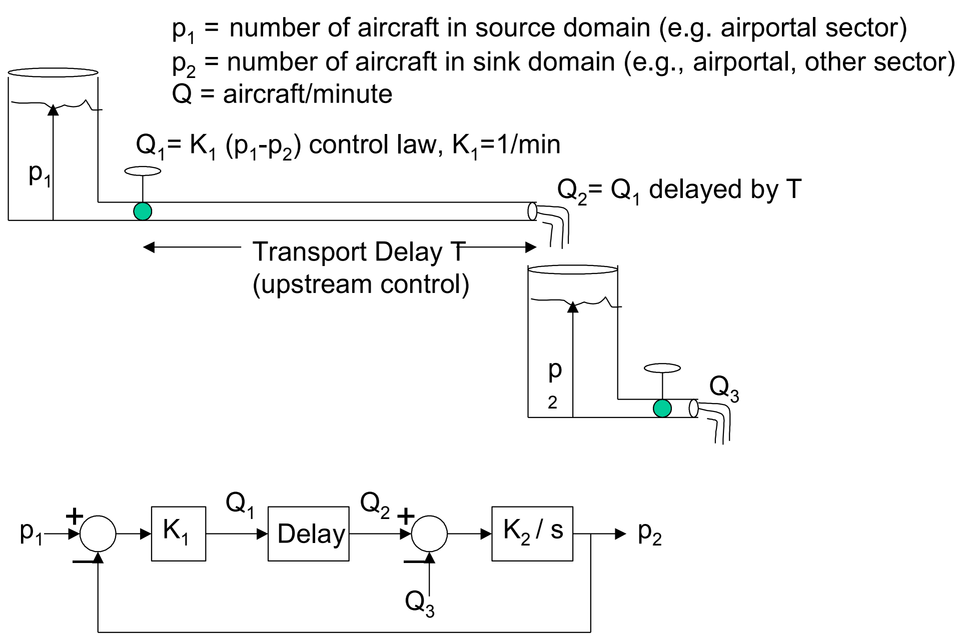


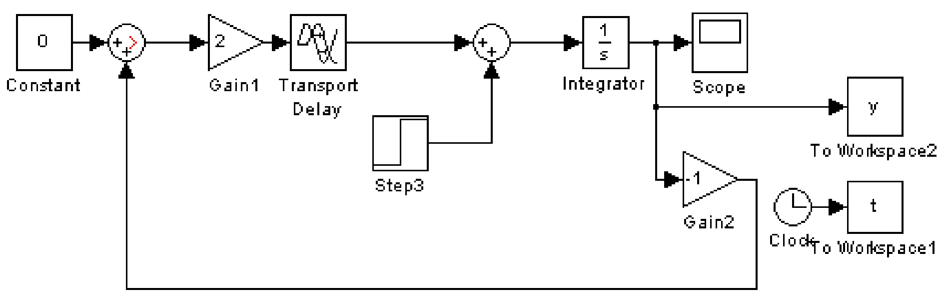
Figure 1. Two-tank flow analogy (upper) and block diagram (lower).

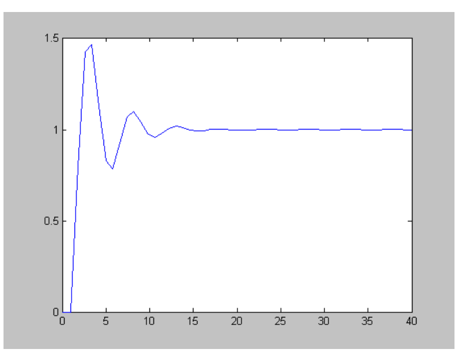
Flow of aircraft from a terminal airspace sector onto an airport can be considered analogous to a liquid flowing from one tank (airspace sector) and emptying into a second tank (airport surface), with a flow control valve at the arrival fix, another emptying out the airport (departures), and a transport delay T (see below relative to its magnitude) between the arrival fix and touchdown.

In Figure 1 the variables p = water level = pressure = number of aircraft in each tank and the variables Q = flow rate = aircraft/min are shown at corresponding points in the diagram. The lower part of the figure puts the same system into a conventional block diagram that can be analyzed. We assume a simple control law that sets the upstream flow rate proportional to the difference between the pressure (aircraft in terminal airspace tank) and that in the airport surface tank.

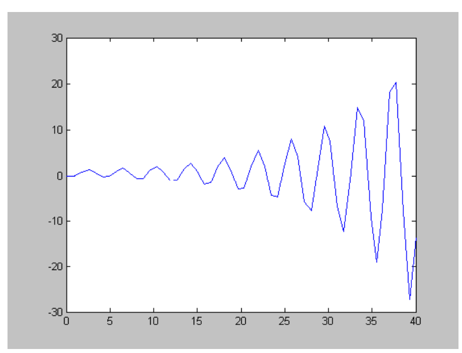
Simulation Demonstration

The response of p_2, the number of aircraft accumulated on the airport surface, to a step change in outflow from the airport (Q_3) is simulated using the Simulink® (MatLab) tool (Figure 2, upper diagram). Such a step change could result from unscheduled departure delays, for example. Since the system dynamics are assumed linear we can treat responses to Q_3 and p_1 as independent, so p_1 is set to be an arbitrary constant. In any case these step responses would be similar to one another.





p_2 response to Q_3 step with K_1=1, T=1, K_2=1



p_2 response to Q_3 step with K_1=2, T=1, K_2=1

Figure 2. Simulink® simulation with transport delay (upper); results (lower).

It is important to consider that real upstream control using CTAS or other prediction tools will estimate Q_2 from Q_1 and try to control Q_2. Thus the effective transport delay would be the difference in touchdown times between actual and estimated touchdown times for each successive aircraft, a time interval much shorter than the 20 minutes mentioned above. The discrepancy might be due to speed and trajectory changes required by separation actions, weather, airport reconfiguration, go-arounds, etc.

At the bottom of Figure 2 are plots for a p_2 response to a Q_3 unit step change when $K_1 = 1$ (meaning that when the difference between number of aircraft ($p_1 - p_2$) is 1, flow per minute would be altered by 1 aircraft per minute). Where the delay (discrepancy) here is 1 minute, and $K_2 = 1$, the in and out flows will differ by one aircraft per minute, and there will be one additional aircraft on the surface in that minute. The simulation result is shown to be stable but with significant overshoot. When K_1 is increased to 2 the p_2 variable goes unstable. One can see that the variables Q_1 and Q_2 will follow similar patterns except as linearly transformed by the block diagram reverse transformations.

Generalization

These effects can be generalized by reference to a gain-phase or Bode diagram (Figure 3). Here the net phase lag is the sum of phase shifts from the integration (90 deg) and the transport delay. Then the net loop gain (shaded circle) at the frequency where phase shift is 180 deg (meaning the closed loop is positive) is a function of the integration and the product of coefficients K_1 and K_2, as shown. Insofar as the shaded circle falls below a loop gain of one, the system is stable. For such a system the safety margin (called gain margin) is labeled in the figure.

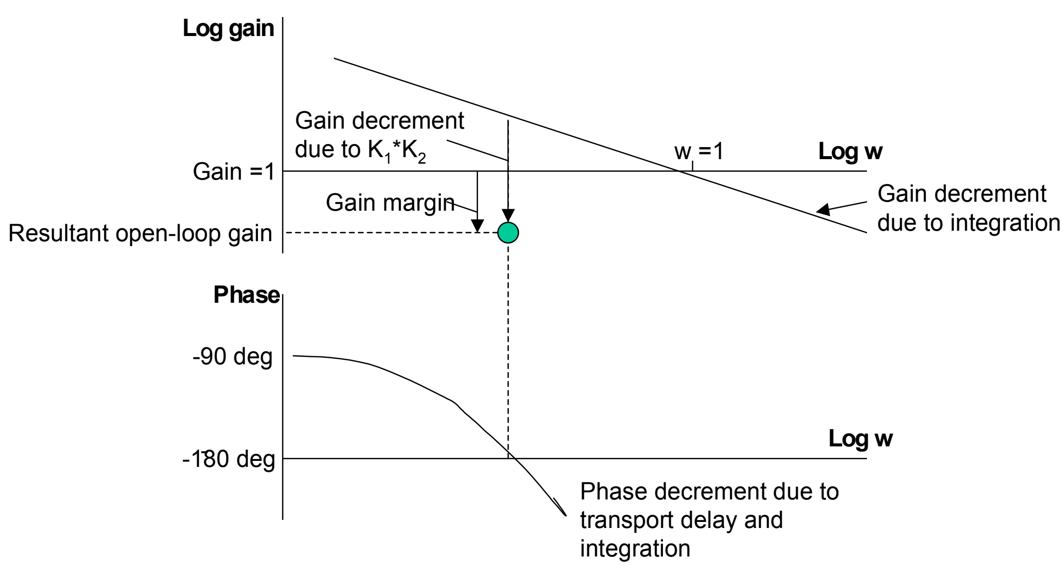


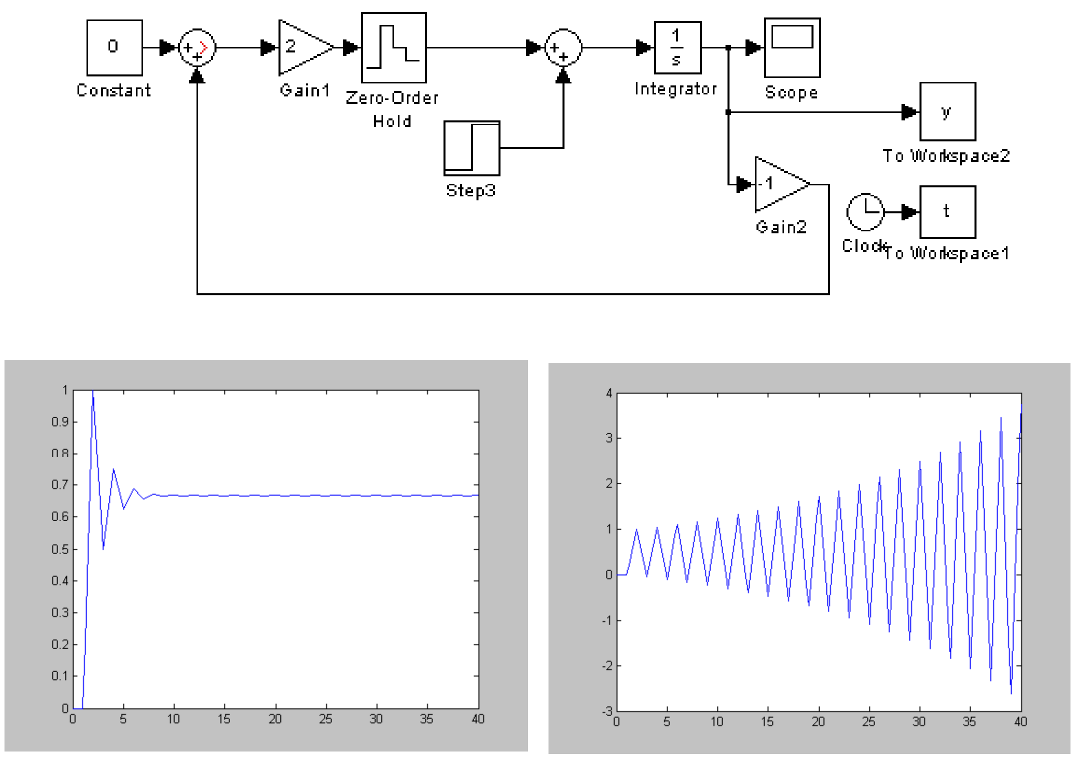
Figure 3. Gain-phase (Bode) diagram generalizing the tradeoffs between gain coefficients and delay time.

For such a system the damping coefficient can be approximated by a second order linear system (which this is not) as $1/ [2(K_1K_2T)^{0.5}]$, and similarly the undamped natural frequency can be approximated by $(K_1K_2 / T)^{0.5}$. In that case if $K_1K_2 = 1/T$, then damping is critical (no overshoot) and natural frequency is proportional to $1/T$.

Sample-and-Hold Effects on Stability

If instead of a time delay (discrepancy) we substitute a sample-and-hold element, meaning that the upstream control agent takes a sample and then holds that value continuously until the next sample, we get an effect close to that of a transport delay (Figure 4). The hold time T in this case assumes that prediction of Q_2 from Q_1 is perfect. Figure 4 (top) shows the simulation setup. The bottom left plot shows the p_1 response to a Q_3 unit step change when $K_1 = 1.5$, $T = 1$ (minute hold between samples) and $K_2 = 1$, while that at right shows the p_1 response to a Q_3 unit step change when $K_1 = 2.05$, $T = 1$ and $K_2 = 1$. In this system the response for $K_1 = 2.0$ is marginally stable. The destabilizing effects for transport delay and sample-hold are roughly additive.

Sample-hold may be the more likely concern for NGATS if continuous upstream control is utilized. It should be noted, however, that the K_1 values assumed here are probably significantly greater than what is contemplated. Furthermore, flow control is now performed manually and the control loop is not continuously closed in quite the same fashion as what is assumed here, which might be relevant if automatic control is contemplated.



p_2 response to Q_3 step with K_1=1.5, T=1, K_2=1 p_2 response to Q_3 step with K_1=2.05, T=1, K_2=1

Figure 4. Simulink® simulation with sample-hold (upper); results (lower).

In summary, this is a precautionary note, hopefully not representative of what will be designed into NGATS. Similar thinking can be applied to the effects of transport delay and sample-hold in control of aircraft separation [4].

References

[1] Gilbo, E.P., Airport capacity: representation, estimation, optimization. IEEE Trans. Control System Technology, Vol. 1, No.3, Sept. 1993.

[2] Gilbo, E.P., Optimizing airport capacity utilization in air traffic flow management subject to constraints at arrival and departure fixes. IEEE Trans. Control System Technology, Vol. 5, No.5, Sept. 1997.

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[4] Sheridan, T., Burki-Cohen, J. and Corker, K., Human transient into-the-loop simulation for NGATS. Paper presented at the AIAA Conference on Modeling and Simulation, Keystone CO, 21-23 Aug, 2006.