# COMPRESSOR STABILITY MANAGEMENT IN AIRCRAFT ENGINES

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**Keywords**: *Compressors, Stability, Auto-correlation, Gas Turbines*


## Abstract

*The safety for modern gas turbine engines can be greatly improved with the development of accurate on-line measurement to gauge the aerodynamic stability level for fans and compressors. This paper describes the development and application of a robust real time algorithm for gauging fan/compressor aerodynamic stability level using over-the-rotor dynamic pressure sensors. This real time scheme computes a correlation measure through signal multiplication and integration. The algorithm uses the existing speed signal from the engine control for cycle synchronization. The algorithm is simple and is implemented on a portable computer to facilitate rapid real-time implementation on different experimental platforms as demonstrated both on a full-scale high-speed compressor rig and on an advanced aircraft engine. In the multi-stage advanced compressor rig test, the compressor was moved toward stall at constant speed by closing a discharge valve. The stability management system was able to detect an impending stall and trigger opening of the valve so as to avoid compressor surge. In the full-scale engine test, the engine was configured with a one-per-rev distortion screen and transients were run with a significant amount of fuel enrichment to facilitate stall. Test data from a series of continuous rapid transients run in the engine test showed that in all cases the stability management system was able to detect an impending stall and manipulated the enrichment part of the fuel schedule to provide stall free transients.*




## NOMENCLATURE

| | | |
|---|---|---|
| ASC | = | Active Stall Control |
| C (t) | = | Auto-correlation measure |
| DV | = | Discharge Valve (used to throttle the compressor) |
| i | = | Index |
| P | = | Pressure Signal |
| Pr | = | Pressure ratio |
| t | = | Current sample time |
| RPM | = | Compressor shaft speed (revolutions per minute) |
| shaft | = | Shaft time period |
| wnd | = | Correlation window size |

## 1 Introduction

Rig and engine test processes and in flight operation and safety for modern gas turbine engines can be greatly improved with the development of accurate on-line measurement to gauge the aerodynamic stability level for fans and compressors. Having a stability management capability during engine development testing would ensure stall free operation resulting in enhanced engine acceleration / thrust capabilities and significant reductions in development cycle time by avoiding attendant hardware failures due to unexpected surge events in the compression components.

Since reliable early stall warning measurement systems and algorithms are in the experimental phase, modern high stage loading compressors are currently being designed with conservative steady state stall margin requirements that have to include effects due to deterioration, engine control tolerance, engine transient/thermal effects and inlet distortion. Conservative stall margin requirements result in efficiency penalties that impact the overall engine fuel burn and temperature margins. A robust and reliable stability management system could alleviate the conservative stall margin requirements by active regulation of routine control devices available, such as variable stator and/or fuel schedules and bleed and/or exhaust nozzle actuation.

Active compressor stall control by suppressing the stall inception phenomenon was originally proposed by Epstein et al. [1] in 1986. The stall inception process was investigated further by Camp et al. [2], Hoying et al. [3], Breuer et al. [4] and Garnier et al. [5]. Camp and Day proposed two typical stall inceptions: a long-wavelength pattern referred to as 'modal oscillation' and a short-wavelength pattern typically of the order of one or two blade passages referred to as 'spike'. Using numerical experiments, Hoying [3] showed that the short length-scale inception process was linked to the behavior of the blade passage flow field structure, specifically the tip clearance vortex and claim that a criterion for stall inception for the short length-scale phenomena requires that the tip vortex trajectory be perpendicular to the axial direction. Tryfonidis, et al. [6] investigated pre-stall behavior of several high-speed compressors and proposed a new technique based on spectral analysis of the spatial Fourier harmonics of measured case wall pressures. Day et al. [7] reported test results from four high-speed compressors and suggested that an alternative approach to active stall control is to disregard the physical details of the flow generating the incoming signals and to simply pay attention to deriving a stall risk index from the sum of all the inputs. Hoenen and Arnold [8] proposed a monitoring algorithm for the prediction of unstable compressor operation that involves analyzing the signal patterns of dynamic pressure transducers mounted above the first rotor. As the compressor approached stall, the amplitude of the blade passing frequency was reduced but new frequency peaks occurred and grew until stall. By blanking out the blade passing frequency and its harmonics from the spectra and by means of numerical differentiation, taking absolute values and finally integration, the stability parameter was calculated from the remaining signal.

In addition to the study of pre-stall behavior, a variety of active control devices have been designed and tested in the last few years. One popular way of compressor operating range extension has been obtained by using air injection for stabilizing compressor flow in the vicinity of the tip gap. The stabilizing effect of air injection can be achieved in two different ways. Starting a constant air injection at several circumferential positions when an on-line monitoring stability parameter derived from high frequency pressure data exceeds a threshold can eliminate 'spikes' and delay the onset of stall to lower mass flows as demonstrated by Freeman et al. [9] in a single spool turbojet engine. In addition to constant blowing, modulated air injection to damp out modal disturbances that start growing at certain operating conditions near the stall line to further extend the operating range has been reported by Spakovszky et al. [10], Weigl et al. [11] and Suder, et al. [12].

Leinhos et al. [13] used a combined approach of both constant and modulated air injection into the low-pressure compressor (booster) in a twin spool turbofan engine. The turbofan engine studied had a tip critical first booster rotor that exhibited different types of stall inception at different speeds. At low speeds spikes initiated the instability, while there were some weak indications for a modal type stall inception in the mid-speed regime and strong evidence that a disturbance rotating at LPC rotor frequency caused stall in the high speed region [14]. In their test, the injected air was either taken from an external source or from bleed ports at the high-pressure compressor exit.

Tahara et al. [15] proposed a unique stall-warning index based on pressure signals by high response transducers on the casing wall at the rotor leading edge. Tests conducted on a research compressor with both uniform inlet and with inlet distortion revealed that their stall correlation degradation first appeared at the mid chord location and advanced toward the leading edge with decrease in flow coefficient. The correlation degradation increased monotonically with decrease in the flow coefficient and had the potential to generate a stall-warning signal sufficiently in advance of spike inception for the stall avoidance actuation to respond in a timely manner.

This paper describes the development of a robust real time fan/compressor aerodynamic stability management system using over-the-rotor-tip dynamic pressure sensors. The real time algorithm used for gauging the aerodynamic stability level is based on the method first reported by Dhingra et al. [16] in 2003. This real time scheme computes an auto-correlation measure through signal multiplication and integration. The auto-correlation, reported herein, has a value of unity for a purely periodic signal (stable operation) while the correlation of a completely chaotic or random signal (unstable operation) would be zero. The algorithm uses the existing speed (RPM) signal from the engine control for cycle synchronization. The auto-correlation measure is computed for individual pressure transducers over rotor blade-tips. The auto-correlation system samples a signal from a pressure sensor (Kulite) at 200 KHz. A window of seventy-two samples is used to calculate the auto-correlation showing a value of unity along the compressor operating line, decreasing to zero when the compressor is in surge. At a test developed pre-set threshold level of the auto-correlation, the stability management system sends an electrical signal to the engine control, which in turn takes corrective action using the available control devices to move the engine away from surge.

The algorithm is simple and is implemented on a portable computer to facilitate rapid implementation on different experimental platforms such as compressor rigs or fielded gas turbine engines. It is very adaptable into an engine's electronic control system. This real-time scheme for detecting compressor instabilities was demonstrated on both in a full-scale high-speed compressor rig test and in an advanced aircraft engine test.

In the multi-stage advanced compressor rig test, the stability management system was successfully demonstrated by attempting to stall the compressor by increasing the compressor pressure ratio at constant corrected speed by closing the rig discharge valve (throttling to stall). Test data will be presented that shows that the auto-correlation was able to sense the onset of stall and trigger corrective actions in sufficient time to avoid compressor surges.

Rapid transients, often referred to as bodes, were run in a full-scale engine test. The engine was configured with a one-per-rev distortion screen and transients were run with a significant amount of fuel enrichment to intentionally stall the engine. Test data from a series of eight continuous rapid transients (bodes) run in the engine test will be presented that show that the correlation method performed consistently in all the testing. In all cases, the impending stall was detected by the auto-correlation. The auto-correlation managed by triggering / deactivating the enrichment part of the fuel schedule resulting in stall free bodes.

## 2 Correlation Measure

The approach to the correlation measure was conceived and continues to be developed at the School of Aerospace Engineering, Georgia Institute of Technology [16]. This approach is based on a measure that permits an assessment of the operating line proximity to the compressor stability limit. The correlation measure quantifies, in a way, the available stall margin. The measure is essentially truncated auto-correlation, and is simply referred to as the correlation measure. The measure is defined on the basis of the repeatability of the pressure time-trace, as observed by a sensor located over the rotor. The pressure time-trace is mostly periodic when the compressor is operating away from the surge line. However, as the boundary of unstable operation is approached, this periodicity progressively deteriorates.

This phenomenon is illustrated in Figures 1 and 2 that show pressure time-traces obtained on the axial compressor research rig. The trace corresponding to the compressor operation in a safe regime is presented in Figure 1. The compressor is operating far away from stall and a comparison of the current pressure trace to one shaft period ago shows strong similarity between the two traces. Some differences, due to phenomena like natural turbulence and measurement noise, are to be expected. However, as shown in Figure 2, when the compressor operates close to its stall boundary, the pressure traces vary significantly from one cycle to another. The loss of periodicity is quantified via the correlation measure, which can be expressed as

$$C(t) = \frac{\sum_{i=t-wnd}^{t} \left(P_i \cdot P_{i-shaft}\right)}{\sqrt{\sum_{i=t-wnd}^{t} P_i^2 \cdot \sum_{i=t-shaft}^{t} P_{i-shaft}^2}} \quad (1)$$

Although wnd can be any value up to the number of samples in one shaft rotation, the experience to date is that a value, which spans three to four blades, is a good choice. By its very mathematical definition, the correlation measure is bound by 1 from above and -1 from below. When the behavior of the compressor is accounted for, the measure usually stays between 1 and 0, with a value of 1 implying perfect repetition of the pressure trace.

The validity of the correlation measure based approach has been previously established and reported by Dhingra et al. [16] and [17]. It has further been examined and clarified in a paper by Dhingra et al. [18]. The application of the signals obtained in Figures 1 and 2 is illustrated further in Figures 3 and 4. Figure 3 shows a set of typical speed lines from the experimental compressor rig. The compressor map depicts the pressure ratio plotted against inlet corrected mass flow rate. The corrected speed is represented by the parameter "n" in the figure. Several points with increasing pressure ratio and decreasing mass flow rate along a speed line "n5" are shown in different colors in the figure.

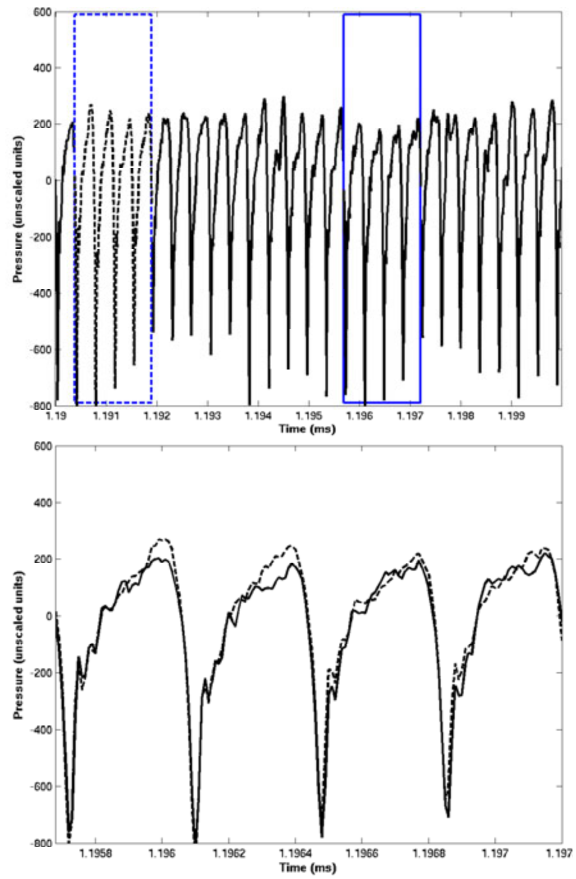


**Figure 1: Illustration of periodicity as observed by over-the-rotor dynamic pressure measurements when the compressor is operating far away from stall.**

Figure 4 shows the auto-correlation results at several different points along the compressor speed line as the compressor is throttled starting from a low pressure ratio marching up toward stall. Test data for the auto-correlation shown in Eqn. (1) was acquired using over-the-rotor-tip Kulites in the test rig. The auto-correlation color scheme in Figure 4 corresponds to the color scheme for the individual points shown in Figure 3. When the compressor is far away from stall (Dark Blue color in Figures 3 and 4 corresponding to a stall margin of 12.2 %) the time wise fluctuation of the auto-correlation is between 0.9 and 1. As the compressor approaches stall (Red color in Figures 3 and 4) not only does the value of the auto-correlation decrease but the fluctuations (randomness) increases suggesting the approaching of stall (chaos) in the compressor.

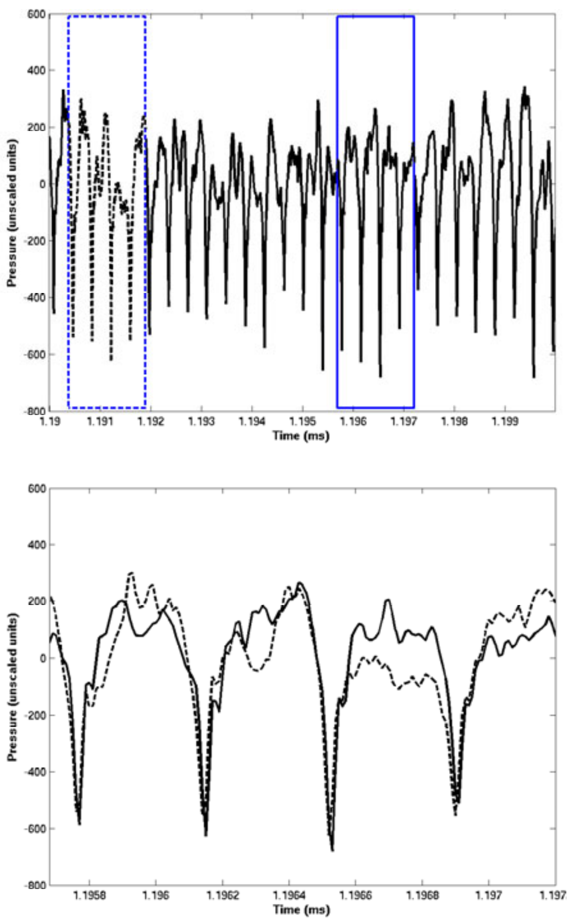


**Figure 2: Illustration of loss of periodicity when the compressor is operating close to stall.**

This trend, in general, is true for all stages in the compressor. Hence, each stage's correlation measure, and not just the one for the stalling stage, is available to be used to gauge the stability status of the whole compressor. Naturally, for monitoring purposes one would select from among the most responsive stages, and one would keep the number of selected stages to a minimum. While in the rig and engine test applications reported in this paper, monitoring just one location sufficed, it is possible that some future applications may require monitoring more than one stage and possibly even more than one circumferential location in a stage to provide reliable coverage at all speeds and altitudes, and with inlet distortion. Further, it is expected although perhaps not yet demonstrated, that due to radial communication within a blade row, variation in the correlation measure will be recognized by a tip sensor even if the flow breakdown is initiating in the hub region of that blade row.

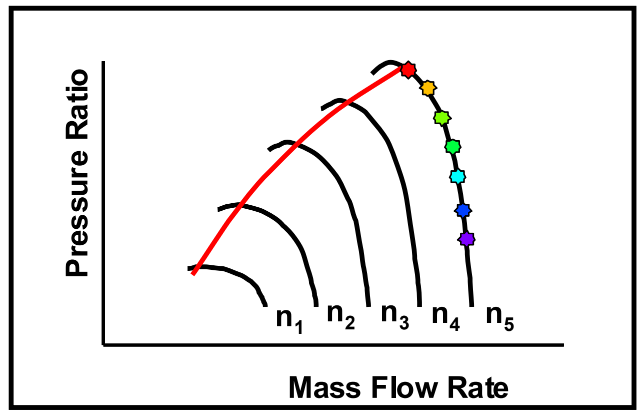


**Figure 3: Compressor map for Georgia Tech experimental compressor rig.**

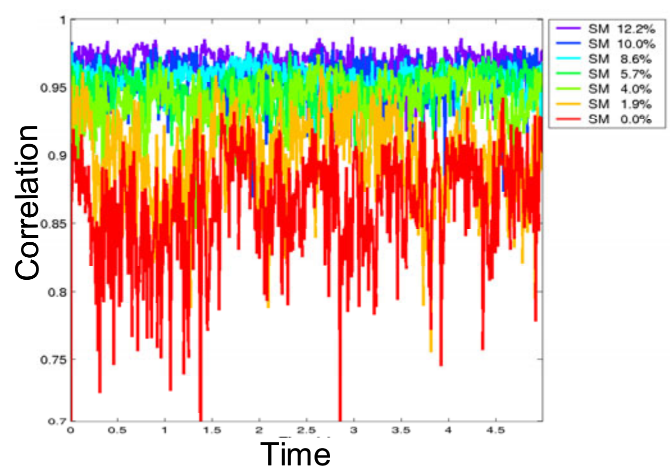


**Figure 4: Auto-correlation signals at key points along the compressor speed line "n5" calculated using the auto-correlation in Eq. (1).**

Following this general introduction of the correlation measure, the paper now turns to its application to a compressor for an advanced aircraft gas turbine engine.

## 3 Multi-Stage Compressor Rig Application

The active stall control correlation measure was applied in an advanced six-stage compressor rig test. The compressor has an inlet guide vane and two variable stators. The stability management system was demonstrated while attempting to stall the compressor by closing the discharge valve and increasing the overall pressure ratio at constant speed.

In the first case the compressor pressure ratio was increased at constant speed (throttling to stall) by closing the rig discharge valve (DV), and in the second case the compressor variable guide vanes were locked in the open position at high speed on the compressor operating line and the compressor speed reduced until the compressor reached its stability limit.

As observed by Dhingra et al. [16] and Tahara et al. [15], the axial location of the dynamic pressure sensors (Kulites) plays a prominent role in the early detection of impending stall. The experiments by Tahara et al. [15] showed that the pressure signals near the rotor leading edges are most effective near stall when the tip leakage vortex trajectory shifts towards the leading edge of the adjacent blade as explained in the paper by Hoying [3]. However, the experimental results presented by Dhingra et al. [16] showed that the pressure signals near the rotor blade mid-chord location provide the largest sensitivity for the correlation measure.

In addition to the usual performance instrumentation, all the compressor blades were instrumented with two over-the-rotor-tip leading edge dynamic pressure sensor (Kulites) placed 180 degrees apart circumferentially and one rotor mid-chord Kulite that was circumferentially in line with one of the two leading edge Kulites. There was no mid-chord Kulite over the compressor Rotor 5 due to mechanical interference.

As described above, the correlation algorithm uses the existing RPM signal from the rig control for cycle synchronization. The auto-correlation measure is computed for individual pressure transducers over rotor blade-tips. The algorithm is simple and was implemented on a portable real-time computer to facilitate rapid implementation.

The auto-correlation system sampled a signal from a dynamic pressure sensor (Kulite) at 200 KHz. In terms of Kulite responsiveness, a response rate that is ten times the blade passing frequency is required for reliable and repeatable results when examining blade-to-blade pressure fields. A window of seventy-two samples is used to calculate the auto-correlation showing a value near unity along the compressor operating line, decreasing to zero when the compressor was in surge. At a pre-set threshold level of the auto-correlation, the stability management system sent an electrical signal to the rig control, which in turn took corrective action by opening the discharge valve to move the compressor away from surge.

In the rig test, the Kulite at mid-chord over Rotor 2 worked the best for the autocorrelation and its signal was used consistently for all the active stall control (ASC) tests. All tests were conducted with clean inlet.

Figure 5 shows the increase in compressor pressure ratio (throttling) as the rig discharge valve is closed at 96% corrected speed. Figure 6 shows the distribution of the dynamic pressure signal and the corresponding auto-correlation with time as the compressor is throttled transiently towards stall. The data presented in Figure 6 represents the “open loop” condition. The term “open loop” implies that when the auto-correlation drops below a threshold (~0.4 in this case), it sends an alarm (shown as a red color line in the figures below) to the control but no action is taken to avoid the surge. The considerations that enter into setting the level for the threshold is that it be above the correlation measure at stall, and that it secures the proper lead times for the control to react.

The “open loop” test case was used to confirm that the auto-correlation is able to capture the onset of stall accurately. It also helps determine the time, in this case 25 mili-seconds (approximately 1% remaining stall margin as shown in Figure 5), required to react to the alarm sent to the control by the auto-correlation as illustrated with the expanded time scale in Figure 7. The expanded time scale near stall in Figure 7 spans 0.2 seconds, relative to 3 seconds time span presented in Figure 6.

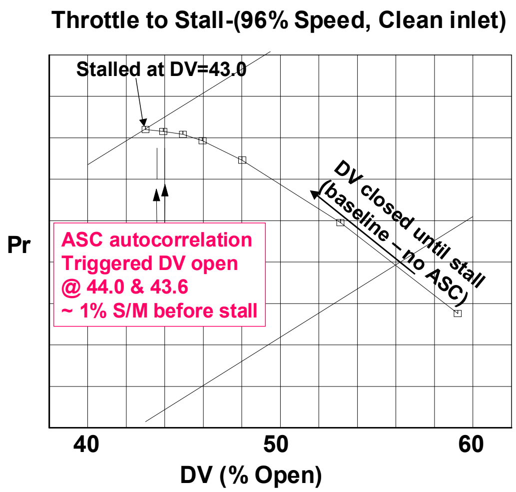


**Figure 5: Compressor speed line at 96 % corrected speed.**

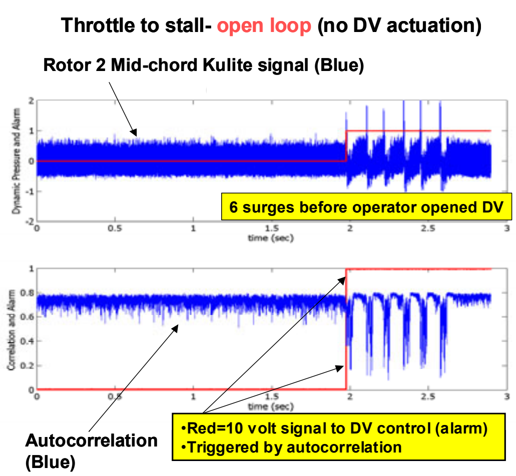


**Figure 6: Distribution of Rotor 2 mid-chord Kulite signal (Dynamic pressure) and Auto-correlation with time as the compressor is throttled to stall.**

After confirming that auto-correlation signal was accurately representing the compressor mode of transient operation while being throttled to stall, the rig test proceeded with "closed loop" testing where the correlation signal automatically activates the control to open the discharge valve to lower the compressor pressure ratio and move the compressor away from surge. The transient operation of the compressor in "closed loop" is represented in Figure 8 by the Rotor 2 mid-chord Kulite traces. Two-second Kulite and the auto-correlation traces before and after the auto-correlation has sensed and activated the stall control mechanism, in this case the discharge valve, is presented in this Figure 8.

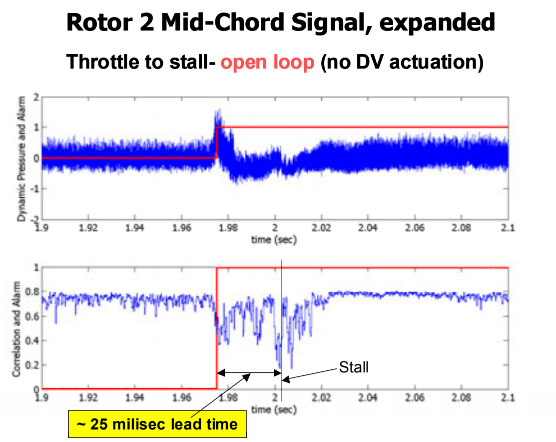


**Figure 7: Expanded time scale from Figure 6 for Kulite signal and auto-correlation.**

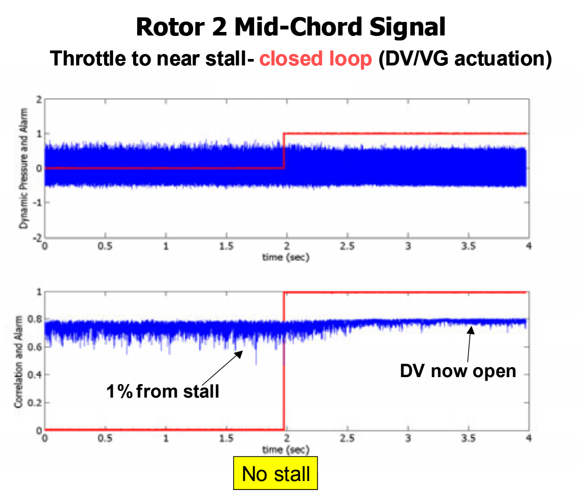


**Figure 8: Active Stall control demonstration in the compressor rig**

Figure 9 shows the same Kulite and corresponding auto-correlation traces using an expanded time scale (0.2 seconds span). When the auto-correlation dipped below the preset threshold of 0.4 (note that there is a blue line correlation trace below the red line alarm signal in Figure 8 and 9 which represents the time wise location of the sounding of the alarm), the compressor discharge valve was automatically activated to open preventing compressor surge. The transient throttling of the compressor to stall at 96% speed was repeated and the stability management system (closed loop) was demonstrated successfully again.

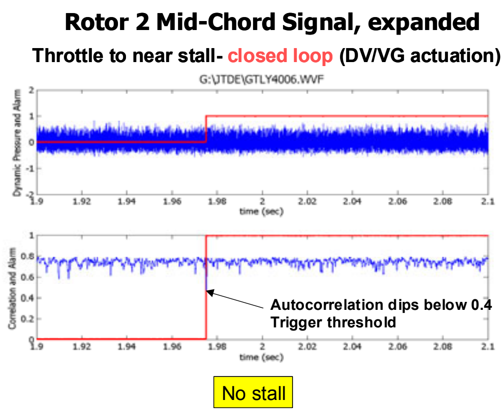


**Figure 9: Expanded time scale from Figure 6 illustrating no compressor stall of after the alarm was sent by the auto-correlation to open the exit discharge valve.**

While not shown in detail herein, similar successful results were obtained on the compressor rig during deceleration with the variable stators held fixed at their starting speed nominal position. One should appreciate the wear and tear that could be avoided on a vehicle by demonstrating stability limits using the correlation measure in place of actual hard stalls. Also, controls manipulation of the discharge valve (DV) as demanded by the correlation measure could well be employed to simulate engine type transient migration of the operating line in a component rig test.

## 4 Engine Application

Rapid transients, often referred to as bodes, are frequently run with enriched fuel flow in full-scale engine test to demonstrate excess stability margins during engine certification or qualification tests. This type of testing is used herein to demonstrate the feasibility of the stability management system.

The compressor on the engine, different from the prior discussed rig application, has seven-stages and was instrumented with one row of over-the-rotor tip Kulites at the leading edges of all the rotors and mid-chord Kulites over Rotors 2, 3 and 6. Unfortunately, during the initial engine tests with ram inlet conditions, many of the Kulites downstream of stage 3 mal-functioned. Rotor 2 (green) and Rotor 3 (red) leading edge Kulites appeared to provide a strong signal for the auto-correlation and Figure 10 shows the auto-correlation from these two Kulites. Based on the results shown in Figure 10, Rotor 3's leading edge Kulite was deemed to provide a better auto-correlation and was used for all the tests to demonstrate and trigger the stability management system. A block diagram illustrating the overall system operation is shown in Figure 11.

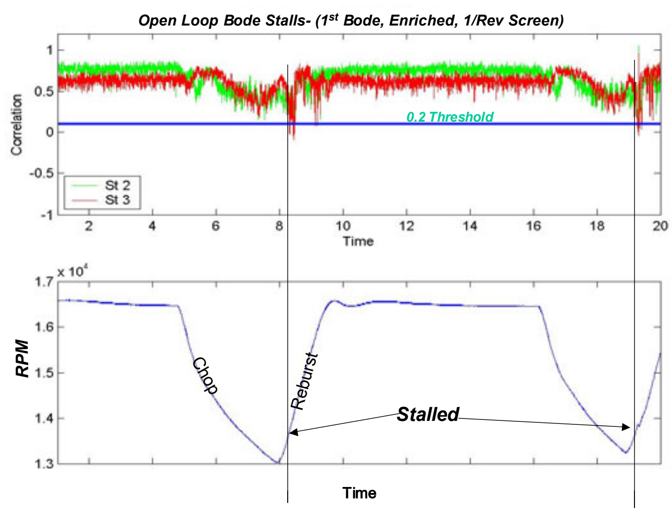


**Figure 10: Measured auto-correlation from stage 2 and stage 3 rotors.**

The engine was configured with a one-per-rev inlet distortion screen and transients were run with a significant amount of fuel enrichment to intentionally force the engine to stall. A typical result from an engine transient is presented in Figure 12. The transient begins with an instantaneous reduction in speed from high power operation to idle with the engine operator pulling the throttle back, commonly referred to as a “chop”, followed by an immediate increase in speed by pushing the throttle forward from idle to high power commonly referred to as a “re-burst”. A continuous sequence of a chop and a re-burst is sometimes referred to as a “bode”.

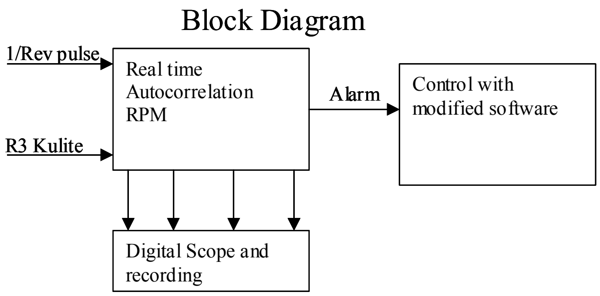


**Figure 11: Schematic of stability management system on the engine.**

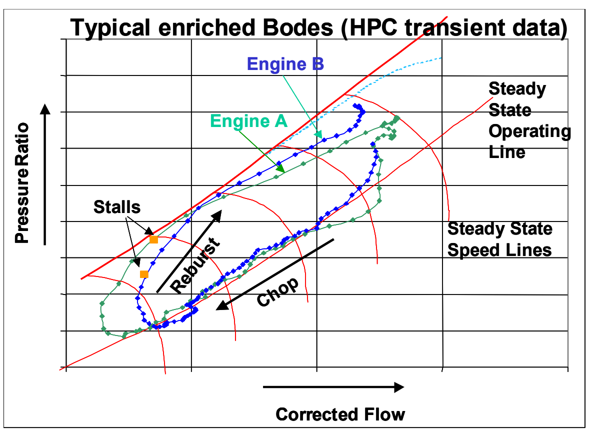


**Figure 12: Typical rapid engine transients with enriched fuel flow illustrating the migration of the compressor operating line toward stall.**

The steady state speed lines, operating line and stall line are shown in red in Figure 12. A typical transient path the compressor operating lines take for two engines A and B is presented in blue and green in the same figure. The path is closely related to the thermal state of the engine during the chop and the re-burst. The engine operating line is seen to follow the steady state operating line during the chop followed by a significant increase in pressure ratio at the turnaround point as the engine begins to accelerate. Recall, that in-addition to thermal effects, the engine is running with inlet distortion which has lowered the stall line to some extent and the rapid increase in fuel (enrichment) back-pressures the compressor further resulting in engine stalls at the turnaround speed as illustrated in Figure 12. The difference in the transient paths the compressors in engine A and engine B took during bodes can be attributed to engine-to-engine variation and unsteady measurement accuracies.

Test data from a series of continuous rapid transients (bodes) run in the engine test with the ASC system in the “open loop” control mode is presented in Figure 13. The figure shows a series of 9 bodes. There was approximately a 15 second span between each bode. The compressor goes through a stall each time at the turnaround speed during the first two bodes followed by stall free operation for the rest of bodes.

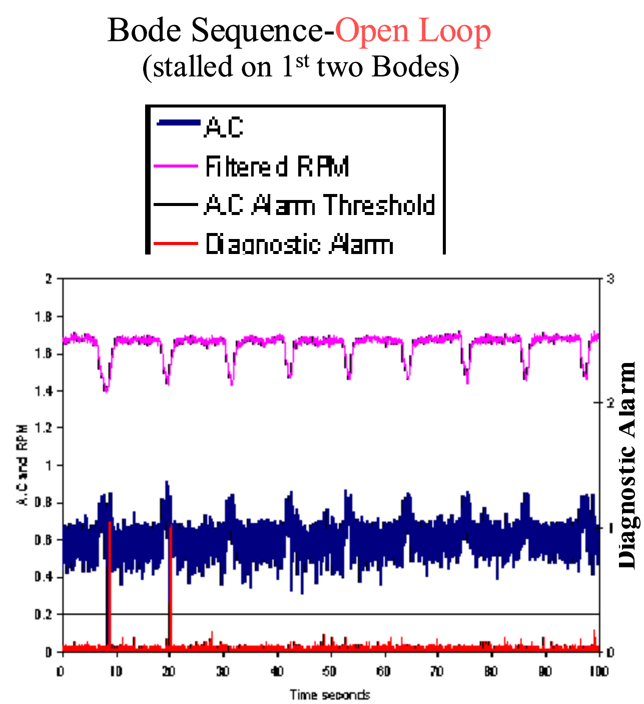


**Figure 13: Engine transients showing RPM in purple, auto-correlation in blue and alarm signals from the auto-correlation in red.**

Figure 14 shows an expanded view of the first stall during the engine transient from Figure 13. The auto-correlation threshold to trigger the alarm was set at 0.2 in the engine test. An alert signal that a stall precursor had been identified by the auto-correlation resulted in an alarm, which consists of a 10-volt signal, being sent to the control as shown in red in Figures 13 and 14.

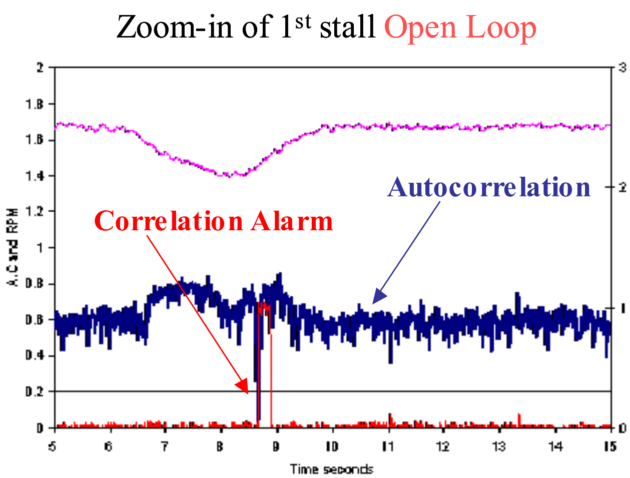


**Figure 14: Expanded time-wise view of first stall during engine transients. (Top line represents RPM).**

Figure 15 shows test data from the auto-correlation signal and the corresponding compressor speed (RPM) with an expanded time scale using functioning Kulites over compressor stage 3 and stage 6. The engine was running in the "open loop" control mode while this data was acquired. Recall, that the threshold for the stall precursor alarm using the auto-correlation was set at 0.2. The time available between the sounding of the alarm prior to stall and actual compressor stall was determined to be approximately 30 to 40 mili-seconds using the auto-correlation for stage 3.

With the working of the auto-correlation validated using stage 3 Kulite data and the stall recovery time identified, the engine was run next with the stability management system in the "closed loop" control mode. As shown before in Figures 12, 13 and 14, the stalls encountered by the compressor during the bodes occurred during the acceleration (re-burst) part of the transient locally near the turn around point from idle to high power. Thus, the control software was programmed to accept the 10-volt stall alarm trigger and respond by de-activating (cutback) the enrichment part of the acceleration fuel schedule.

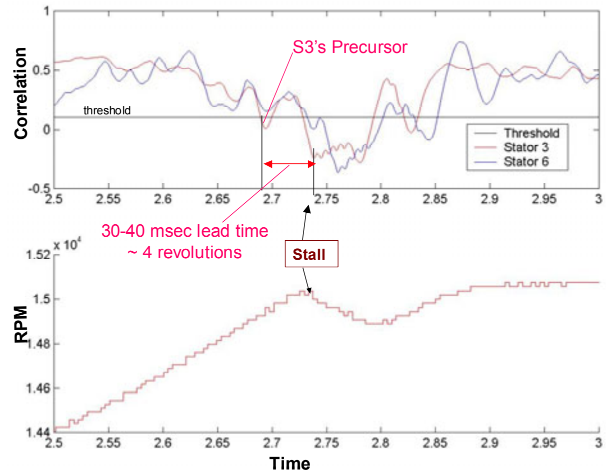


**Figure 15: Alarm from the autocorrelation gives between 30 to 40 mili-seconds (~4 revolutions) reaction time before stall.**

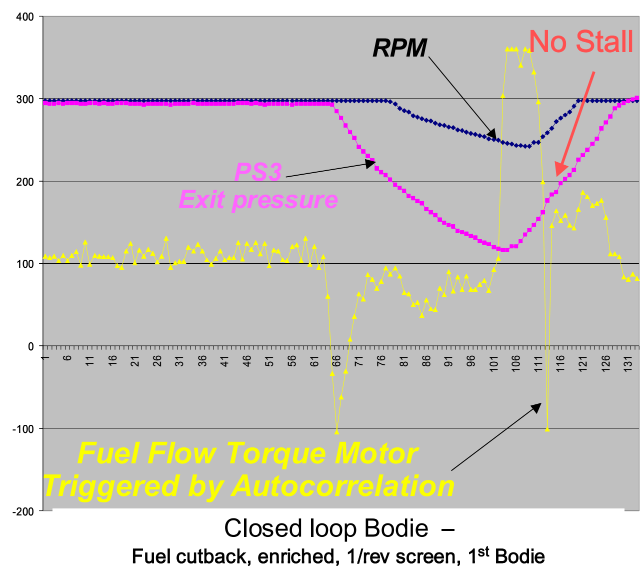


**Figure 16: Stability management used to cutback the fuel schedule during acceleration and avoid stall during engine transients.**

Figure 16 shows the expanded time wise distribution of compressor corrected speed (RPM); compressor exit static pressure (PS3) and fuel flow during the first bode on the engine where the compressor without the stability management system goes through a stall event stall (recoverable stall). The time scale shown in the figure is in ten times the actual value in seconds. In Figure 16, the RPM is shown in blue, PS3 in pink and fuel flow in yellow.

In the test, the operator pulled the throttle back (chop ~ 3 seconds) reducing the fuel flow (initial spike down to idle fuel flow shown in yellow) to the engine at 63 units of time that starts the drop in PS3 followed by the drop in compressor speed (RPM) soon thereafter. The throttle was pushed forward again (re-burst ~ 1.5 seconds) to reach high power at 100 units of time shown by the spike up in fuel flow followed shortly by an increase in PS3 and slightly later by compressor RPM. This time delay between the spike up in fuel flow and increase in compressor RPM can be attributed to the inertia of the compressor disk. At approximately 108 units in time the auto-correlation sensed a stall precursor and sent an alarm to the control to cutback the acceleration fuel flow to the engine as illustrated by the spike down in fuel flow in Figure 16. The engine accelerated (with the deactivated fuel flow enrichment as commanded by the control) through this critical region stall free when previously there used to be a recoverable stall event at this juncture. The fuel flow was restored back to its original enriched acceleration schedule by the control as soon as the correlation measure had recovered to a level above the threshold resulting in stall free engine operation in this local region.

The transient bodes demonstration was repeated again with and without the stability management system. The compressor did not go through any stall event with the system in place. The correlation method performed consistently in all the testing. In all cases, the impending stall was detected by the auto-correlation. The auto-correlation triggered / deactivated the enrichment part of the fuel schedule resulting in stall avoidance.

## 5 Concluding Remarks

This paper suggests that incorporating the compression component stability management system into the electronic controls of an aircraft engine appears to be a viable option to enhance performance and handling characteristics for future developments programs. The results presented in this paper address the fundamental issues about the feasibility, potential and capabilities of an existing auto-correlation technique to interactively manage the stability of an aero engine.

This paper described the development of a robust real time algorithm for gauging the fan/compressor aerodynamic stability level using over the rotor dynamic pressure sensors. The auto-correlation system sampled a signal from a pressure sensor (Kulite) at 200 KHz. A window of seventy-two samples is used to calculate the auto-correlation. At a pre-set threshold level of the auto-correlation, the stability management system sent an electrical signal to the engine control, which in turn took corrective action to move the engine away from surge.

The algorithm is simple and was implemented on a portable real-time computer to facilitate rapid implementation on different experimental platforms such as compressor rigs or fielded gas turbine engines. This real-time scheme for detecting compressor instabilities was demonstrated on both in a full-scale high-speed compressor rig test and in an advanced aircraft engine test and could easily be integrated into an engine's electronic control.

In the multi-stage advanced compressor rig test, the stability management system was successfully demonstrated when attempting to stall the compressor by increasing the compressor pressure ratio at constant corrected speed by closing the rig discharge valve, and when decelerating the compressor on the operating line holding the stators fixed at their starting speed nominal condition.

Successful rapid transients were run on the full-scale engine test. The engine was configured with a one-per-rev inlet distortion screen and transients were run with a significant amount of fuel enrichment to intentionally try and stall the engine. The correlation method performed consistently in all the testing. In all cases, the impending stall was detected by the auto-correlation. The auto-correlation triggered

/ deactivated the enrichment part of the fuel schedule resulting in stall avoidance.

## 6 Acknowledgements

The authors would like to thank GE Aviation for giving the permission to publish this paper.

## References

[1] Epstien, A. H., Efowcs Williams, J. E., Greitzer, E. M., 1986, "Active Suppression of Aerodynamic Instabilities in Turbomachines," AIAA paper AIAA86-1994.
[2] Camp, T. R., Day, I. J., 1998, "A Study of Spike and Modal Stall Phenomena in a Low-Speed Axial Compressor," Transactions of the ASME, 120, pp. 393-401.
[3] Hoying, D. A., Tan, C. S., and Grietzer, E. M., 1998, "Role of Blade Passage Flow Structures in Axial Compressor Rotating Stall Inception," ASME paper 98-GT-588.
[4] Breuer, Th., Servaty, S., 1996, "Stall Inception and Surge in High Speed Compressors," AGARD CP-571 26/1-17.
[5] Garnier, V.H., Epstein, A. H., and Grietzer, E. M., 1992, "Rotating Waves as a Stall Inception Indication in Axial Compressors," ASME Transactions, Journal of Turbomachinery, 113, pp. 290-301.
[6] Tryfonidis, M., Etchevers, D., Paduano, J. D., Epstein, A. H., and Hendicks, G. J., 1995, "Prestall Behavior of Several High Speed Compressors," ASME Transactions, 117, pp. 62-80.
[7] Day, I., Breuer, T., Escuret, J., Cherrett, M., and Wilson, A., 1999, "Stall Inception and the Prospects for Active Control in Four High Speed Compressors," ASME Transactions, 121, pp. 18-27.
[8] Hoenen, H., and Arnold, T., 2003, "Development of a Surge Prediction System for Multi Stage Axial Compressors," 2003, IGTC2003, Tokyo, TS-040.
[9] Freeman, C., Wilson, A. Day, I. And Swinbanks, M., 1998, "Experiments in Active Control of Stall on an Aero engine Gas Turbine," ASME Transactions, Journal of Turbomachinery, 120, pp. 637-647.
[10] Spakovszky, Z., Weigl, H., Paduano, J., van Schalkwyk, C., Suder, K. and Bright M., 1999, "Rotating Stall Control in a High-Speed Stage with Inlet Distortion," ASME Transactions, Journal of Turbomachinery, 121, pp. 510-524.
[11] Weigl, H., Paduano, J., Frechette, A., Epstein, A., Greitzer, E., Bright, M., and Strazisar, A., 1998, "Active Stabilization of Rotating Stall in a Transonic Single Stage Axial Compressor," ASME Transactions, Journal of Turbomachinery, 120, pp.625-636.
[12] Suder, K., Hathaway, M., Thorp, S., Strazisar, A., and Bright, M., 2001, "Compressor Stability Enhancement Using Discrete Tip Injection," ASME Transactions, Journal of Turbomachinery, 123, pp. 14-23.
[13] Leinhos, D., Scheidler, S., Fottner, L., Grauer, F., Hermann, J., Mettenleiter, M., and Orthmann, A., 2002, "Experiments in Active Stall Control of a Twin-Spool Turbofan Engine," ASME paper No. 2002-GT-30002.
[14] Hoss, B., Leinhos, D., and Fottner, L., 2000, "Stall Inception in the Compressor System of a Turbofan Engine," ASME Transactions, Journal of Turbomachinery, 122, pp.32-44.
[15] Tahara, N., Kurosaki, M., Ohta, Y., Outa, E., Nakakita, T., and Tsurumi, Y., 2004, "Early Stall Warning Technique for Axial Flow Compressors," ASME paper No. 2004-GT-53292.
[16] Dhingra, M., Neumeier, Y., Prasad, J.V.R., and Shin, H. W., 2003, "Stall and Surge Precursors in Axial Compressors," presented at 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Alabama.
[17] Dhingra, M., Armor, J., Neumeier, Y., and Prasad, J.V.R., 2005, "Compressor Surge: A Limit Detection and Avoidance Problem," presented at AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, California, 2005.
[18] Dhingra, M., Neumeier, Y., Prasad, J.V.R., Breeze-Stringfellow, A., Shin, H-W. and Szucs, P.N., "A Stochastic Model for a Compressor Stability Measure," ASME Turbo Expo, 2006, GT2006-91182.