Investigation of Pre-Stall Mode and Pip Inception in High Speed Compressors Through the Use of Correlation Integral

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Abstract. Five high speed compressor configurations are used to identify pre-stall pressure signal activity under clean and distorted inlet conditions, and under steady injection and controlled injection conditions. Through the use of a nonlinear statistic called correlation integral, variations in the compressor dynamics are identified from the pre-stall pressure activity far before variations (modal or pip) are observed visually in the wall static pressure measurements. The correlation integral not only discerns changing dynamics of these compressors prior to stall, but is now used to measure the strength of the tip flow field for these five high speed compressors. Results show that correlation integral value changes dramatically when the stall inception is modal; and it changes less severely when the stall inception is through pip disturbances. This algorithm can therefore distinguish from the pre-stall pressure traces when a machine is more likely to stall due to pips versus modes. When used in this manner, the correlation integral thus provides a measure of tip flow strength. The algorithm requires no predisposition about the expected behavior of the data in order to detect changing dynamics in the compressor, thus no pre-filtering is necessary. However, by band-pass filtering the data, one can monitor changing dynamics in the tip flow field for various frequency regimes. An outcome of this is to associate changes in correlation integral value directly to frequency specific events occurring in the compressor, i.e. blade length scale events versus long length scale acoustic events. The correlation integral provides a potential advantage over linear spectral techniques because a single sensor is used for detection and analysis of the instabilities.

Introduction

In recent years the focus of compressor stall research has centered around identifying a physical process which induces rotating stall in compressors. With recent advances in the on-line identification of stall, and with successful strategies in place to extend the operating range to lower mass flow rates; active stall control in a research compressor environment is a reality. With this advent of active stall control methods, a reliable pre-stall indicator is becoming a necessity for future applications in compressors.

The existing methods to identify stall precursive events are often categorized based on the detection of long length scale (modal) or short length scale (pip) disturbances. In a paper by Tryfonidis et al. (1995), the emphasis is to study long length scale phenomenon that leads to rotating stall. Other investigations by Day (1993), Park (1994), Camp & Day (1997), and Schulze (1997) reflect the detection of short length scale (pip) activity in several high speed compressors. In a recent report by Weigl (1997) on the active stabilization of high speed compressors, several pre-stall data sets showed modal activity, then a controller was used to suppress the modal waves, and subsequent pip activity instigated the controller to go unstable. With this in mind, it would be advantageous to develop analysis and prediction techniques that detect both short and long length-scale disturbances which lead to rotating stall.

Bright (1997) presented a nonlinear methodology for the detection of pre-stall behavior in a limited set of high speed compressors. This methodology, called the correlation integral method, is based on nonlinear dynamics and chaos theory. This pre-stall detector identified in experimental data the underlying nonlinear dynamics of the fluid flow prior to the stall event. The correlation integral value was shown to change dramatically hundreds of rotor revolutions prior to the stall event in several test cases. It was also presented that the traveling wave energy algorithm (see Tryfonidis), when applied to the same data, did not detect changing pre-stall behavior until after the correlation integral value changed. From this prior paper it was inferred that something inherently nonlinear was occurring in the pressure data prior to stall inception that the correlation integral perceived; and that this

1 Through discussions with Ivor Day, this short length-scale activity in the data was observed in the controlled data sets.
nonlinearity eventually triggered an occurrence of modal stall onset. Figures 1a and 1b, as shown below, are taken from this previous paper (Bright, 1997) to compare directly the application of the traveling wave energy method and the application of the correlation integral method to the same pre-stall pressure data. Figure 1a shows the traveling wave energy begin to grow around 200 rotor revolutions before stall. This method used all 8 pressure sensors spaced 45 degrees apart for calculation of this traveling wave energy. Figure 1b shows the sharp decline of the Correlation Integral value at approximately 600 rotor revolutions prior to stall as determined by a single pressure sensor.

In the present paper, we will attempt to broaden the discussion of this nonlinear methodology through a study of experimental results from a variety of compressor configurations. We will identify in these compressors the short length scale or long length scale phenomenon present prior to rotating stall through visual inspection of the pressure traces. With this data we will then use the correlation integral to clearly show from a single pressure trace the onset of instabilities leading to stall. We will also attempt to show in the correlation integral results some differences in the reaction of the correlation integral value during modal stall onset versus pip stall onset. The experimental results will include examples from single stage transonic compressors with clean and distorted inlet flow, and with steady and controlled air injection.

Background. Several researchers have identified short length scale or pip disturbances in their compressor data. [most notably, Day(1993)] A robust method for detection of these pip instabilities during the onset of rotating stall, however, has not been presented. There has been a great number of investigations into the fluid physical stalling mechanisms in compressors, (McDougall, Hoying, Paduano, Longley), especially with distortion present. In a recent paper by Camp and Day (1997), a measure of critical incidence of the blade tip is performed. Based on experimental measurements, a simple stall inception model is given to explain the formation of spikes and modes. It was stated in this paper that both pips and modes can occur in the same compressor, sometimes even simultaneously. Also, it was stated that in a single stage compressor, the occurrence of modes or spikes was influenced by changing the radial distribution of rotor incidence. When the critical incidence of the rotor is exceeded, the rotor stalls.

An alternative technique is described below to monitor changing flow field conditions and to measure the strength of the tip flow field during the onset of rotating stall. This measure is sensitive to changes in long and short length-scale disturbances and provides some insight into the inception of pips and modes.

Background on Correlation Integral Analysis

To begin to understand the type of physical phenomena initiating the creation of modes and pips, it is necessary to have a metric sensitive to both spatial and temporal dynamic changes. Recently, we presented a possible metric, namely the correlation integral (Bright, 1997) whose value showed a marked decline prior to stall in a limited set of high-speed compressor data. The correlation integral (CI) is commonly applied to highly nonlinear systems and relies on
an M-dimensional reconstructed pseudo-attractor from a single sensor using time delays. The CI is defined by:

$$CI(N, R) = \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} H(R - \|y(t_i) - y(t_j)\|)$$

where $y$ represents the M-dimensional reconstructed time series, $N$ is the number of data points used in the reconstruction, $H$ is the Heaviside step function, and $\| \|$ is the $L_\infty$ norm. (see Grassberger for a full discussion of this algorithm). What is essential about this algorithm is the inter-point distances $\|y(t_i) - y(t_j)\|$ between all pairs of points in the signal and the reference distance $R$. The $CI(N,R)$ includes in its calculation an auto-correlation length which eliminates consideration of any points too close in time to one another. The correlation integral can be viewed as a measure of the average density at some scale $R$ of the data (Lerner, 1996). Another view is that the CI is the fraction of inter-point distances which are within a reference distance $R$. As the nature of the oscillations in the data change, the inter-point distances and the corresponding CI will dramatically change.

The correlation integral was computed for all data sets presented in this paper using an embedding dimension $M$, of 10 and a reconstruction delay of one; thus the dimension of the pseudo-attractor is quite high. In the earlier paper we chose a smaller value of $M$ and a larger reconstruction delay. However, papers recently published by Kugiumtzis (1996) and Wu (1995) discuss the validity of selecting a high embedding dimension in order to accurately reproduce the underlying dynamics of a system. The use of a larger $M$ value accentuates the decline in total amplitude of the CI value and does not effect where in time the CI value begins to decline. For this reason it is hard to compare results from our earlier paper since a small $M$ value was used. A larger $M$ value significantly improves the CI method for our present application since changing dynamics of the flow field are further enhanced. However, as $M$ is increased above a value of 10, nothing more is gained, and no further "enhancement" is seen in the CI curves. Note only that the same $M$ value is used for every test case.

For all the cases presented the CI was determined for a 5000 point window of data. The window was updated every 1000 points, and the data was sampled at 3 Kilohertz. The endpoint for the last data window was carefully chosen so that it does not include any in-stall behavior.

The key to understanding CI values is the manner in which the pseudo-attractor (or phase plane representation of the signal) changes shape and density with the onset of modes and/or pips. Consider a window of pressure data that is 5000 points long, where the amplitudes of the oscillations in the data are very similar. These regular oscillations force the trajectories of the pseudo-attractor to repeatedly visit the same region. In other words, if the data oscillates with very little variations in amplitude, then the trajectories reside on the outside "skin" of an M-dimensional sphere. This pseudo-attractor will have very high density and most of the distances between pairs of points will be both very small and narrowly distributed. This in turn means that the fraction of distances less than some specified $R$ is large and results in a relatively large CI value. If the amplitudes of the oscillations are significantly different in the next data window, such as during the inception of pips or modes, then the pseudo-attractor will have a broader distribution of distances. In this case, one could visualize the trajectories now entering the "inside and outside" of the sphere, thus, creating longer distances between some pairs, and a lower CI value. When comparing the pressure traces with the CI results it is important to keep in mind that sections of a time trace with relatively small amplitude range contribute small inter-point distances and increase the CI value. Sections of a time trace with relatively large amplitude range contribute large inter-point distances and decrease the CI value.

A specific example of this concept is presented for data obtained in NASA's high speed single stage compressor facility. A description of the compressor and experimental procedure for this example can be found in Bright (1997). The data was taken while the compressor was transitioned into stall through slow closure of the throttle. The data was originally sampled at 20 kHz and anti-aliased filtered at 10 kHz. For this example the data is then low-pass filtered at 500 Hz, generating a signal void of high frequency variations. A pseudo-attractor is reconstructed using 5000 data point windows and the CI computed. Figure 2 shows the CI value for a fixed $R$ as the compressor is ramped into stall. Well

![Figure 2. CI value for Data filtered at 500 Hz](image-url)
before the stall event, the CI maintains a high value until approximately 292 rotor revolutions before stall when it begins a rapid decline.

We now want to look further at what is occurring in the data window just prior to this decline at -292 revolutions versus what is occurring in the data window at stall (0 revolutions). Figure 3a depicts the distribution of all the inter-point distances in the pseudo-attractor for the data window ending at 292 revolutions before stall. Figure 3b is the distribution for the data window ending at stall (0 revolutions). Note that there are over 12 million inter-point distances calculated for a 5000-point pseudo-attractor.

These histograms portray all the possible combinations of inter-point distances between pairs of points for 5000 samples of data. The correlation integral at a fixed $R$ represents the ratio of the area under this curve from $R = 0$ to the fixed value of $R$, versus the entire area under the histogram.

In the first histogram in figure 3a, the compressor operation is stable (albeit nearer to stall and not near choke) and the distances are concentrated around $R = 2.5$. This means that there are very few large inter-point distances. In the window just before stall, the histogram from figure 3b shows that increasing amplitudes caused by developing modal instabilities have created a wider distribution of distances, which are now centered around $R = 5$. Many large inter-point distances are also present, some as high as $R=35$. These results show, most importantly, that the CI curve yields evidence of dynamical changes that are occurring well before stall which are not observed in the pressure traces or from a spectral analysis.

From these observations we can further characterize the growth of inter-point distances before stall and perhaps tie these observations to a physical phenomenon in the compressor. The CI method is next used on band pass filtered data sets. The previous data is now low pass filtered at 100 Hz instead of 500 Hz. Figure 4 shows the CI curve for the filtered 100 Hz data. A marked decrease in the CI curve is not evident until 140 rotor revs before stall, coincident with the observation of modes in the pressure traces.
(commensurate with blade passage frequencies), the Cl value also drops around 100 revolutions before stall. This drop in Cl value at high frequencies also occurs at the same time as the appearance of modes in the data. (see Wang, 1997 and Li 1997). This would point to the occurrence of both blade passage frequency events in addition to low frequency events (below 100 Hz) that occur simultaneously before rotating stall. However, there are events in the 100 Hz to 500 Hz range that are growing and inducing these disturbances before stall. It is this range of frequency events that we will further investigate in our five test cases.

The remaining sections of this paper now describe the experiments performed on the high speed compressors, their compressor operating conditions, and their pre-stall behavior in terms of modal or pip instabilities as seen in the pressure traces. We will also give Correlation Integral results for all the data sets. An explanation for the changes in the CI curves based on the pressure signals is also given. Finally, we conclude with a general discussion of the applicability of the CI method to future research on stall inception processes.

**Experimental Setup and Data Acquisition**

Experimental data was recorded from several compressors in a series of experiments that occurred between 1994 and 1997. All the data sets were collected for various configurations of the high speed single stage compressor rig at NASA Lewis, running either stage 35 or stage 37. Configurations of the NASA stage 35 and 37 compressor included clean inlet conditions, radial distortion, circumferential distortion, steady air injection and controlled injected air upstream of the rotor. All the examples shown were transitioned into stall using a slow throttling maneuver. To specifically identify modal and pip behavior using the correlation integral we will closely study just five test cases from the single stage compressor rig. Case 1 is the stage operating with clean inlet conditions. Case 2 is the stage with 120 degree circumferential inlet distortion. Case 3 is the stage with radial inlet distortion. Case 4 is the stage with radial inlet distortion and steady air injection from 12 high pressure air jets located circumferentially around the annulus at the inlet. Finally, case 5 is the stage with a clean casing and with controlled unsteady air injection from the actuators located at the inlet.

In all test cases, data was acquired using 5 psi range a/c coupled pressure transducers at eight equally resolved locations around the annulus. Although for the analysis using the nonlinear correlation integral method only one sensor is needed, all eight transducers are recorded for comparison with other Fourier spectral techniques. The data was recorded at 3 KHz sampling rate. All of the five test cases shown were taken from the NASA Lewis Research Center Single-Stage Axial Compressor Test Facility which is fully described in Weigl (1997). The NASA Stage 35 test compressor was originally designed as an inlet stage of an eight-stage 20:1 pressure ratio core compressor (Reid 1978, Moore 1980). The stage has a total pressure ratio of 1.82, a mass flow of 20.2 kg/s, a rotor tip speed of 455 m/s, and a rotation frequency of 286 Hz at design speed.

**Stall Transients in Pressure Data**

Pressure data for case 1 is presented in Figure 5 for the stage running with a clean inlet. This is considered our baseline case and as shown the compressor stalls due to modal instabilities which are visible in the pressure traces before stall. At 40 revolutions before stall there appear to be spikes on top of the modes just before stall. This indicates that our high speed stage under normal stalling conditions is considered a “modal” machine since modal instabilities dominate the pre-stall behavior with some added pip instabilities present just before stall.

Figure 5. Pressure Traces for Clean Inlet Case

Figure 6 reveals results from case 2 when the baseline machine is configured with total pressure circumferential inlet distortion. The distortion was introduced with a magnitude of one dynamic head and a 120 degree extent and covered the full blade span. The fine mesh distortion screen was located approximately 10 chord lengths upstream of the rotor. In this case there appear to be pips occurring about 35 rotor revolutions before stall which travel around the circumference twice but do not grow in amplitude. These pips then seem to run into the peak of a mode forming at 33 revolutions and disappear, and the machine again stalls.

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due primarily to modal instabilities. (This experiment is more fully described in Spakovszky, 1998b).

Figure 6. Pressure Traces for Circumferential Distortion

Figure 7. Pressure Traces for Radial Distortion

Test case 3, however, indicates a distinctly different mechanism which induces stall when radial inlet distortion is present. A fine mesh screen was placed 10 chord lengths upstream of the rotor which covered 38% of the blade span in the tip region to create the distortion. (See Spakovszky, 1998a) The stalling mechanism in this case seems to be inherently pip-like instabilities, not modal, as is evidenced in the pressure traces shown in Figure 7 at 40 rotor revolutions before stall. There appear to be pip disturbances that rotate around the circumference of the compressor but do not grow in amplitude until 5 revolutions before stall. Modal instabilities do not appear in these traces at all.

Figure 8 shows the results from test case 4, where the same the radial distortion configuration is in place, however, there is a constant level of steady injected air supplied from 12 injectors located upstream of the rotor. Now the pressure traces indicate modal instabilities appearing before stall at 35 rotor revolutions, whereas the no-blowing configuration showed pips.

Figure 8. Pressure Traces for Radial Distortion with Injection

Finally, test case 5 reveals the clean inlet stage subjected to controlled air blowing to create a damping pattern of the pre-stall modal waves. Although the modal instabilities are damped due to the controlled injected air, it now appears that at 50 rotor revolutions before stall, pip-like disturbances travel around the circumference, collide with the peak of a forming modal wave, and induce modal waves with spikes on top that grow unstable into stall. This is shown in figure 9.

Figure 9. Pressure Traces for Controlled Air Injection
If we examine the compressor speed lines for all these test cases shown in Figure 10, we see a trend in the shape of these curves as we approach stall. For the baseline case, the circumferential distortion case, and the radial distortion case with steady injection, all machines appear to stall at or beyond the peak of the compressor characteristic. The two cases that stall at the peak of the curve seem to exhibit modes with pips. The radial case with injection stalls beyond the peak of the characteristic. For the radial distortion case without injection, which showed only pip behavior, the machine stalls short of its peak. These observations would be similar to those of Camp and Day (1997) and their model of critical incidence.

![Figure 10. Compressor Characteristics for Stage 35](image)

Figure 10. Compressor Characteristics for Stage 35 of the rotor. Additionally, this would point to a higher tip criticality or high tip flow loading on the radially distorted stage. As discussed in the next section, the measure of this tip flow loading is an important aspect of the correlation integral algorithm.

**Application of Correlation Integral to Test Cases**

The CI curves were computed for these 5 test cases in order to gain additional insight into the pre-stall dynamic events occurring in the compressor. Figure 11 shows the CI curve at a fixed R computed from a single sensor upstream of the stage. The compressor configuration is the baseline experiment with a clean casing and no blowing or active control present. From the pressure traces we noted that modal instabilities are visible prior to stall. In the CI curve we notice a gradual but continual decline in its value from 2000 revolutions all the way to stall. The decline in the correlation integral value is due to the inception of modal instabilities far before these modal disturbances appear in the pressure traces. The cumulative drop in CI value from the first inception of these modes to the stall point is about 1.0 orders of magnitude since CI value is on a log 10 scale. We will look at the significance of this value for each test case.

![Figure 11. CI Curve for Baseline Case](image)

Application of Correlation Integral to Test Cases

Figure 12 shows the CI curve for case 2 when circumferential distortion is applied to the stage. At about 1500 revolutions the CI curve declines sharply with continual declines until stall. Inspection of the pressure traces revealed that incipient modal instabilities are seen prior to stall. The sharp decline in CI values for this case are again responding to the inception of modes in the pressure traces before modal behavior is actually seen in the pressure traces. Additionally, in the pressure traces there appear to be spikes or pips forming which travel around the circumference and run into (or perhaps create) a modal disturbance. The cumulative change
In CI value for this case is about 0.8 orders of magnitude from first inception to stall.

Figure 13. CI Curve for Radial Distortion

Radial distortion without blowing (case 3) does not show the obvious growth of modal instabilities, but short length-scale pips are found close to stall. The CI curve shown in Figure 13 is relatively flat for this case with only a modest decrease in its value starting at 800 rotor revs prior to stall. The total CI amplitude change is only on the order of 0.25 as the machine enters stall. This small cumulative change in CI value may be indicative that only short-length scale or pip instabilities are necessary to drive the compressor into stall. From the compressor characteristic this is the only case that appears to reach a critical blade incidence at stall, which is an indicator of pip disturbances due to high tip blade loading.

A sharp decline in the CI curve from figure 14, however, is due to the initiation of modes in the case of radial distortion with air injection at the blade tip (test case 4). This case features a growing oscillation with the approach of stall as seen from the pressure traces in figure 8. At 1000 revolutions, the CI value gradually declines and at 150 rotor revs before stall, the CI curve steeply declines. In this case, the drop in the CI curve appears to result from long length scale modes, with pips appearing on top of the modes in the last few revolutions before stall. The cumulative change in CI value is again 1.0 orders of magnitude.

Figure 14. Radial Distortion With Steady Injected Air

This compressor stage was also operated with active stall control through unsteady air injection. The controlled injection damped out the first two harmonic modes and the surge mode as determined by the traveling wave energy method. (See Weigl, 1997 for a more complete discussion of this experiment). Inspection of the pressure traces from figure 9 shows that the modal activity is suppressed until the last 50 rotor revs, where pips seem to travel around the circumference and excite modal activity before stall. The CI plot in figure 15 shows a continuous decrease in amplitude in CI until the advent of stall. In this case the compressor is operating beyond its normal stalling condition for the entire data set due to the active controller continually suppressing modes through injection. Since the CI value indicates a continuous change in
the dynamics, it is likely that the CI is responding to the continuously alternating actuation from the unsteady fluid of the controlled air jets in addition to the growth of incipient stall. This example also shows that a combination of modes and pips are taking place just before stall, however, the growth of modal activity appears to be the overriding activity. This example does serve as additional evidence that the CI method is sensitive to changing dynamics, whether the source is strictly from steady (distortion screen) or unsteady (controlled air jets) sources. The cumulative change in CI value for this case is on the order of 1.0.

Discussion

A comparison of these cases reveals some striking differences. For all but the radial distortion test case the compressor stalled through strongly modal events. Only in the radial distortion case was no real modal activity seen before stall. In the CI plots, the overall magnitude of change for these modal cases was on the order of 1.0. For the radial distortion case (pip-case), however, the magnitude of CI value varied less than 0.25 orders of magnitude as the stage was transitioned into stall. The CI value in all these cases appears to monitor increased dynamics in the endwall region, and as such, CI is a measure of the strength of the tip flow field.

The dramatic difference in CI amplitude change between pip and modal instabilities is consistent with the concept of "critical incidence" based on the endwall fluid dynamics as suggested by Camp and Day (1997). In the case of radial distortion with no injection, the endwall loading is very high, the blade tip reaches its critical incidence and the compressor stalls through a pip instability before it can reach its peak pressure rise (see Figure 10). For this case the CI magnitude change is small. Only short-length scale or pip instabilities are necessary to drive the compressor into stall. Modes are not given an opportunity to grow and destabilize the system. For the remaining cases the endwall loading is not as high, the blade tip does not reach critical incidence before the compressor achieves its peak pressure rise, and stall occurs primarily through modal instabilities. For these cases the CI magnitude change is large. Modes now have enough time to grow and dominate the flow field, even if pips are present. (Pips and modes are present in the cases where the compressor characteristic just reaches its peak, but the critical incidence is not reached.) If both disturbances are present the CI value will have a cumulative effect, with the largest contribution of amplitude change due to modal disturbances. Hence a combination of different frequency events may work in concert to change the dynamical behavior measured by the CI value prior to stall.

The results shown in figures 2-4 show that filtering the data sets at different frequency bands in combination with this CI method can provide insight into the frequency and/or type of instability inducing stall. The histogram presentation of the correlation integral shows that a combination of low frequency (less than rotating stall frequency) and high frequency (blade passage frequency) events contribute to the induction of stall. The most significant result occurred in the data set which included frequencies from 100 to 500 Hertz. With the exclusion of frequency bands from this range, the prediction of stall became less robust with a shorter warning time. Therefore, something is occurring in the tip flow field in this frequency range that is detected by the correlation integral 1000 or more revolutions before stall. Blade passage frequency events (pips) and rotating stall frequency events (modes) seem to occur simultaneously, and much closer to stall. A benefit of band pass filtering the data is to associate sharp declines in the correlation integral with certain frequency bands. Since a drop in CI value is a cumulative effect of dynamic events, observing specific frequency bands of pre-stall data may help indicate exactly which events are inducing the stall. By pinpointing the frequency bands of events inducing stall, one can specifically eliminate these frequencies through active stall control.

Conclusions

The correlation integral is an effective measure of changes in pre-stall behavior in high speed compressors. This metric is sensitive to the initiation of either pips or modes or a combination of these disturbances. We have shown there is a connection between correlation integral values and changes in either short length scale or long length scale events in the compressor dynamics. The correlation integral can be used as a basis for comparing varied dynamics in distorted in-flow, steady injection and controlled injection test cases and has been shown to detect changes in the fluid tip flow hundreds of revolutions prior to stall in all cases.

A primary result of this investigation is related to the amount that the CI value changes before stall. During modal stall, the CI value dropped 1.0 orders of magnitude from steady operation to the stall point. During pip stall, the CI value dropped only 0.2 orders of magnitude from steady operation into stall. From these results the correlation integral method is indicative of the tip flow strength or criticality of the tip flow. With this in mind, CI value may help determine which control strategy is most effective in stabilizing the compressor. If the CI value changes very slightly before stall, pips are controlling the instability, and steady blowing may be an effective means to strengthen the tip flow and clear the pip behavior out of the tip region. If the CI value changes a large amount before stall, the most effective control strategy may be controlled injection to damp the modal instabilities from growing.
Correlation integral has the potential to determine what types of dynamics to look for in the data, especially if the data is band-passed filtered. This may help indicate the frequency range which contains the most destabilizing disturbances.

Due to the computational complexity of correlation integral, this algorithm is best suited for post-processed data analysis. For on-line experiments, however, an analogous algorithm for correlation integral called *structure function*, (see Provenzale), can be used for real-time application. This technique can also be used to detect modal stall precursors, but is especially suited for predicting pip formation.

An added benefit of correlation integral, as well as structure function, is that they require only a single sensor to accumulate the data. This is advantageous in terms of both robustness and weight.

Finally, the correlation integral may be most useful in explaining pre-stall dynamics when those dynamics are not easily categorized by either pips or modes; as in many of the cases presented here. Perhaps with this insight we may better pursue active stall detection and control techniques for compression systems.

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