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Indicators of Incipient Surge for Three Turbofan Engines Using Standard Equipment and Instrumentation[1]

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ABSTRACT

Engine controller data have been interrogated for indications of incipient surge for three turbofan engines; a large Pratt and Whitney, a large General Electric, and a small Williams International. Versions of these engines are currently operating in the field and all have compression ratios of 18 or greater. The Pratt and Whitney engine was surged only at full power while the other two were surged at partial power and at full power. The interest in this work was in detecting the presence of warning signatures for a current inventory of engines. A constraint was imposed on the experiments to use only existing engine instrumentation. The frequency response of the controller and the engine instrumentation limited the high frequency detection capability to about 100 Hz for the large engines and about 200 Hz for the small engine, For the large engines, it was not possible to detect a surge warning but for the small engine a sufficient warning of incipient surge was detected.

NOMENCLATURE

f = frequency
H = amplitude, modulus squared
P = pressure
T = temperature
t = time

Subscripts

B = burner
CDP = compressor discharge pressure
file = from start of file, start of data acquisition
P = pyrometer
so = from surge onset

1 INTRODUCTION

There have been numerous documented cases (Mitchell and Gilmore (1982), Chambers (1985), Smith (1985), and Campbell (1990)) for which commercial aircraft have inadvertently flown into particle-laden environments and engine operability has become a serious problem. Military aircraft also operate in or around particle-laden environments and have experienced engine difficulties. It is generally accepted that no one would knowingly choose to operate an aircraft in a dust-laden environment. However, when inadvertent venture into adverse environments does take place, it is helpful to have techniques for coping with the potential operational difficulties. Measurement programs have been conducted under controlled laboratory conditions which were designed to investigate the influence of foreign material on the operation of gas turbine engines (Dunn et al. (1987(a)), Batcho et al. (1987), Dunn et al. (1987(b)), Kim et al. (1992), and Dunn et al. (1994)) and to obtain information regarding operational procedures. Results of these measurements have been found to be consistent with in-flight experiences. A much more detailed account of the material presented in this paper can be found in Baran and Dunn (1995).

A segment of the work noted above was devoted to determining for an existing fleet of turbofan engines whether or not the instrumentation currently installed on those engines was capable of detecting an incipient surge. It is well known that rotating stall precedes surge and that stall occurs at a frequency consistent with the high compressor rotational speed (or 1/2 of that speed), e.g. McDougall, et al. (1990), Garnier, et al. (1991), Haynes, et al. (1993). However, the results just noted were generally obtained in low speed research compressors. Tryfonidis, et al. (1995), report results for nine high-speed compressors, all but one of which was a research rig compressor. The only engine data discussed in that paper were obtained using the very low compression ratio (5:1) Viper engine. These authors found significant differences that could be attributed to compressibility and/or geometry. Very limited data appear in the open literature that are applicable to full-scale engines with compression ratios approaching those of the engines used herein. Burwell and Patterson (1985), reported the results of measurements obtained at AEDC for full-scale engines and concluded that their observations were not consistent with those found in low speed compressor research rigs. Day and Freeman

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(1994), report the results obtained using a Viper engine. They concluded that useful information about stall and surge could be obtained from low speed compressor rigs, but they also found some significant differences between the rig and the engine environments (even for the low compression ratio of their machine). The constraints placed on the measurements presented here are very different from those placed on a low speed compressor rig experiment: there exists a fleet of engines that operate at very high compression ratios by comparison to research rigs and they have an existing instrumentation package. Under some situations these engines are operated in unfavorable environments. The intent of our work was to determine what we can learn about incipient surge under these constraints.

The procedure used was to monitor the engine controller parameters during a surge event at a frequency consistent with the particular instrument, and then to search the pre-surge portion of the data history using the FFT power spectrum for an indication of an early warning of surge. As previously noted, only customary engine instrumentation could be used for this purpose. The frequency response of the instrumentation will be described for each engine investigated.

The Pratt and Whitney and the General Electric engines discussed herein were both large thrust axial compressor turbofan engines. The Williams engine was also a turbofan engine, but it has a low pressure axial and a high pressure centrifugal compressor.

2 DESCRIPTION OF EXPERIMENT

The experiment was designed to determine: (a) whether or not the existing engine instrumentation could provide useful information regarding incipient surge, (b) techniques for regaining control of the engine during surge, and (c) operational procedures with a deteriorated engine. During the surge event, the controller parameters were monitored at a frequency of approximately twice the frequency response of the instrument.

The measurements were conducted in a sea level air cooled noise suppression facility that was previously described in Dunn, et al. (1987 (a),(b)). This facility was designed to be a research cell which would allow one to safely put operating engines into stressful situations. There are several different techniques that previous authors have used to induce surge in an engine, and these are described in the references cited in the Introduction. Because the problem of interest here was one of aircraft operability in adverse environments, surge was induced by systematic exposure (for several short periods of time) of the engines to precisely controlled amounts of dust-laden airflow. At the conclusion of each interval of exposure, a rapid throttle excursion from full power to idle and back to full power over a 6 to 8 second time period was performed to determine the sensitivity of the engine to surge. Detailed internal engine inspections were performed prior to and during the measurement program as described below.

2.1 Pre experiment and during experiment internal inspection of engines

Prior to exposing the engines to particulates, each of the subject engines were inspected. In the case of the General Electric engine, the split case construction enabled easy access for pretest measurements of the compressor blade tip clearance and documentation of the condition of the blades. The Pratt and Whitney engine and the Williams International engine had undergone overhaul prior to initiation of the measurement program and the blade clearances and the component conditions were within specifications.

During the course of the measurement program, the engines were routinely shutdown after each segment of particulate exposure. At this time, the fan, the combustor, the late stages of the high compressor, the high-pressure turbine vanes and blades, and the low turbine were inspected using a video bore scope. These bore scope inspections permitted photographic documentation of the condition of the engine before and after each segment of the experiment. As previously noted, rapid throttle excursions were routinely performed to test the sensitivity of the engine to surge. During exposure to particulates, the deteriorating condition of the engine was reflected in a changing operating point, and was apparent in the behavior of such standard engine measurements as compressor discharge pressure (P_{CDP}), burner pressure (P_B), and pyrometer temperature (T_P) among others.

Upon completion of the experiment, each engine was torn down and measurements of the compressor blade tip clearances, the amount of material removed from the compressor and fan blades and the removal location, the condition of the blade outer air seal, and the condition of the turbine vanes and blades were obtained. The combination of pre-test inspections, bore scope inspections, throttle excursions, observations of the dynamic engine behavior throughout the experiments, and post-test inspections provided a history of engine condition.

2.2 Nature of engine damage and cause of surge condition

Each of the engines surged as a result of exposure to a particulate-laden environment. Damage modes that precipitated surge included erosion of the compressor blade tips and leading edges, erosion of the compressor outer air seal, erosion of the diffuser vanes (for the Williams International engine), and material deposition on the high-pressure turbine vanes. The relatively slow to develop (by comparison of other ways normally used to cause an engine to surge) partial blockage of the turbine flow path by deposition of material was the most immediate and most important cause of surge for all three engines. Compressor blade and diffuser vane erosion occurred over a significantly longer time scale.

2.3 Data acquisition

The data acquisition system (DAS) consisted of an IBM compatible computer along with a Keithley 500 intelligent acquisition system. The ASYST scientific and engineering software package was used for data acquisition, processing, and display. Each engine has its own standard set of engine parameter measurements available at the controller. These standard engine parameters were the measurements monitored during the course of the experiments along with a number of rig parameters.

Data were acquired in the following format; (a) all available engine parameters were continuously sampled in the 0.05-1 Hz range during the entire experiment, and (b) a subset of the engine parameters was sampled in parallel at a higher rate in the 50-400 Hz range (depending upon the particular engine) during a surge event. Those engine parameters sampled at the higher frequency provided the database used to develop the surge precursor information. The instruments sampled at the higher frequency were as follows: (1) for the Pratt and Whitney engines, P_{CDP} and P_B were sampled at 50 Hz, (2) for the General Electric engines, P_{CDP} and T_P were sampled at 200 Hz, and (3) for the Williams engines, P_{CDP} was sampled at 400 Hz. For these measurements, the sampling frequency was dictated by the frequency response of the standard engine instrumentation.

The high sampling frequency data were acquired in one of two modes: (1) capture mode or (2) continuous mode. The entire experiment can be considered to be contained in an experiment window defined by the activation and shutdown of the low sampling frequency DAS. Time is clocked relative to DAS activation. In capture mode, the data were first stored in RAM and not saved unless triggered to do so. This trigger occurred when the rate of change of compressor discharge pressure exceeded a specified threshold value characteristic of surge. In this way, only the data window about the trigger event was written to a data file. This was the preferred mode of high-frequency data acquisition. In continuous mode, the engine parameters were sampled and written directly to data files.

3 DATA ANALYSIS

Post-test data processing and engineering analysis were performed on a Sun Sparc Station 10. As noted earlier, the intent was to interrogate the data for indicators of incipient surge. The aforementioned engine parameters represent those which were most likely to provide indicators of surge based on their relative frequency response compared to the other standard engine instrumentation available.

Information contained in a data file was temporally referenced to the beginning of the file. This was a logical choice for the capture mode of high frequency DAS operation. Time references to DAS activation or surge onset were also used to relate events to one another. Within a given data file, a portion of the file was analyzed (i.e., prior to surge onset or during surge) and is referred to as the observation window. In order to perform an FFT analysis, the data were processed over a time interval (FFT window) containing 2^n (n-bit) data samples. For an initial screening of the data from all three engines, a few independent choices of the size and placement of the FFT window within the observation window were sufficient.

3.1 Observations during engine surge

Examples of data collected during surge for the three engines are presented in Figs. 1-8. For each of the three engines, the responses of the engine parameters exhibited a periodic character during surge which was clearly evident in the time domain. By performing an FFT analysis on those data, a calibration of the spectral analysis method was possible. The spectral character of some of these data was useful in guiding the surge indicator analysis effort to be described in Section 3.2.

3.1.1 Pratt and Whitney engine

All of the surges experienced with this engine were at full power with a high compressor speed of approximately 13,000 rpm (215 Hz). The sampling frequency selected was 50 Hz based on the estimated frequency response of the on-board instrumentation. A typical compressor discharge pressure (CDP) history is shown in Fig. 1 for the Pratt and Whitney engine. The burner pressure and CDP track each other consistently. As is well known, engine surge is characterized by a rapid depressurization of the compression system and can be accompanied by the inability to control the engine or by flame out (especially at high altitude). In this particular example, the engine surge event was non-recoverable as the engine was unable to obtain a stable operating point once the surge event had been initiated. The event consisted of many individual surges which are illustrated in Fig. 1. These take the appearance of periodic recovery/surge cycles. Flame out did not occur in this case or in any other of the engine surge events encountered during this measurement program.

Details of the periodic character during engine surge are also illustrated in Fig. 1. The sampling frequency of 50 Hz was selected based on the estimated frequency response of the installed pressure transducer. The local maximum and minimum of each cycle were not known accurately. A rough 'peak-to-peak' estimate yields a surge frequency of ~10 Hz. The surge frequency can be found by performing an FFT analysis on the periodic character of the compressor discharge pressure history during surge. Such an analysis was performed for this example and the resulting spectra is shown in Fig. 2. A pronounced peak is clearly visible at ~9 Hz, consistent with the visual estimate in the time domain.

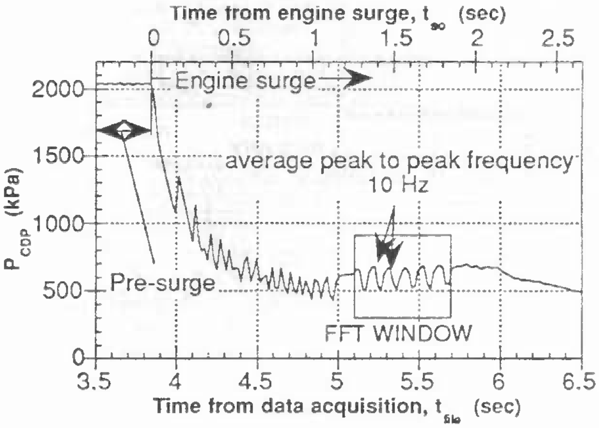

Fig. 1 Typical compressor discharge pressure (CDP) history during engine surge for a P/W engine

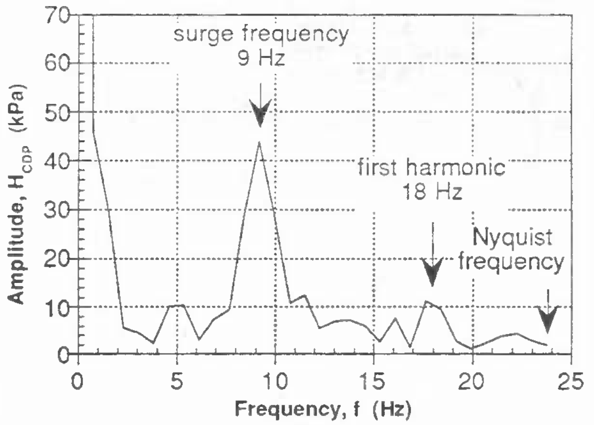

Fig. 2 FFT spectra of the periodic character of CDP during engine surge for a P/W engine

3.1.2 General Electric engine

The surge events for this engine were experienced at full power with a high compressor speed of about 14,500 rpm (240 Hz) and at part power with a high compressor speed of about 13,600 rpm (225 Hz). The sampling frequency selected based on the estimated instrumentation frequency response was 200 Hz. A typical compressor discharge pressure history just prior to and during surge is presented in Fig. 3. Immediately after the initial large pressure decrease which contains several surge events, the engine begins a series of brief recoveries. Recovery can only be sustained for a period of about one half second, then the surging resumes at a frequency of approximately 10.2 Hz. After four of these recovery/surge cycles, a more sustained engine recovery period was observed. However, at about 9 seconds and long before the initial pressure could be re-achieved, the throttle was retarded in order to reestablish a stable

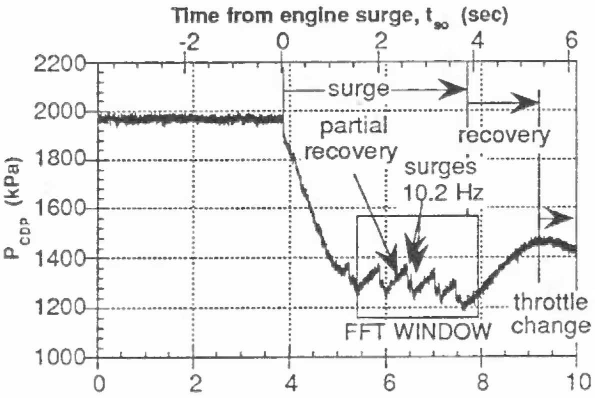

Fig. 3 Typical compressor discharge pressure (CDP) history during engine surge for a GE engine

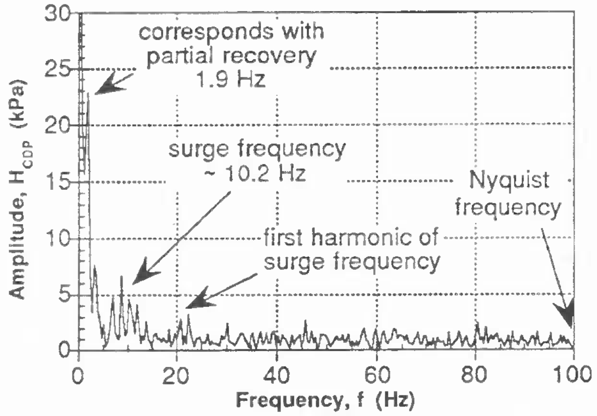

Fig. 4 FFT spectra of the periodic character of CDP during engine surge for a GE engine

operating point. The events noted on this figure as surges correspond with the release of individual fireballs from the exhaust pipe as observed on video cameras and as observed in the pyrometer temperature history to be discussed later.

The FFT analysis of the data shown in Fig. 3 is presented in Fig. 4. The frequency of the recovery cycle occurs at about 1.9 Hz as anticipated by simply looking at the data. The events corresponding to the exiting of fireballs and referred to as surge events occur in the 10 to 10.5 Hz portion of the FFT spectrum. A number of other local peaks are also observed which contain harmonics of the observed cycles in the time domain as well as other frequencies embedded in the CDP signal. The increased resolution of the frequency domain in this example is a result of the larger sample size (9-bit or 512 points) contained in the FFT window compared to that in the previous example.

The control system of the General Electric engine uses a pyrometer (which was not used on the Pratt and Whitney engine) that views a white patch painted on the suction surface of each of two high-pressure turbine blades. The pyrometer temperature (T_P) history corresponding to the CDP history (Fig. 3) is presented in Fig. 5. A number of significant temperature spikes are evident in the data throughout that portion of the time history corresponding to the surge events. The small spikes which are evident in the pre-surge event data continue to be present throughout the data history. The video camera results show that the large spikes correspond precisely to the passage of fireballs from the exhaust pipe. The surges were recorded on video tape at a recording speed of 60 frames/sec. which is a sufficiently high frequency to detect passage of the individual fireballs. For the General Electric engine, the fireballs occurred in pairs as is evident in the T_P history. The time interval between the fireball pairs corresponds precisely to events noted on the CDP time history.

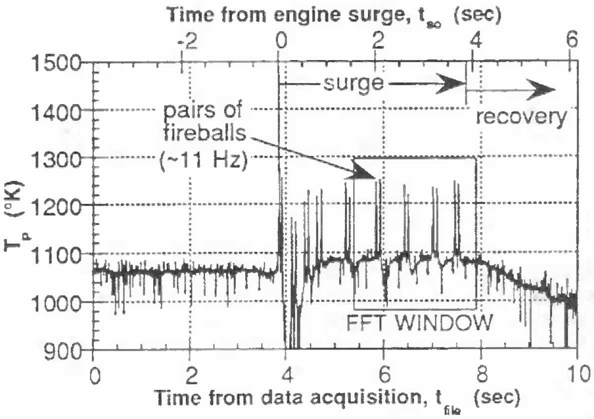

Fig. 5 Typical pyrometer temperature (T_P) history during engine surge for a GE engine

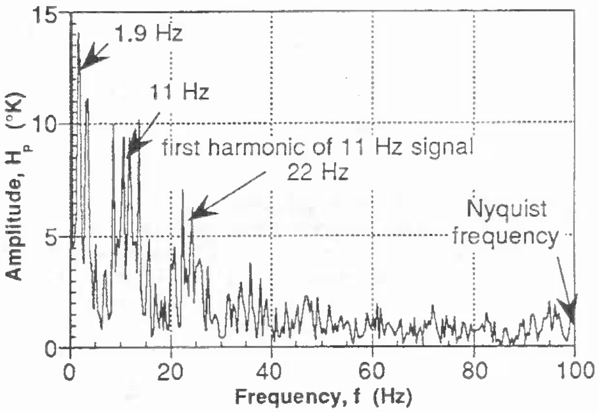

Fig. 6 FFT spectra of the periodic character of T_P during engine surge for a GE engine

An FFT analysis of the T_P time history is presented in Fig. 6. The frequency of initiation of surge (and thus the first of the pair of fireballs) corresponds to the recovery time of a little less than 0.5 seconds as was illustrated on Fig. 5 for the CDP, and shows up on the FFT at 1.9 Hz in the frequency domain. The spike at 3.8 Hz is the first harmonic of the 1.9 Hz peak. There is a grouping of four peaks centered at about 11 Hz, which is consistent with the average interpair frequency observed in the time domain. Another grouping of two relatively strong peaks centered at ~22 Hz corresponds to the first harmonic of the preceding group.

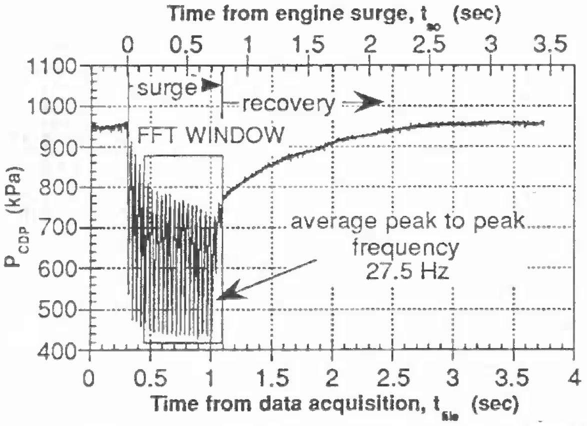

Fig. 7 Typical compressor discharge pressure (CDP) history during engine surge for a Williams engine

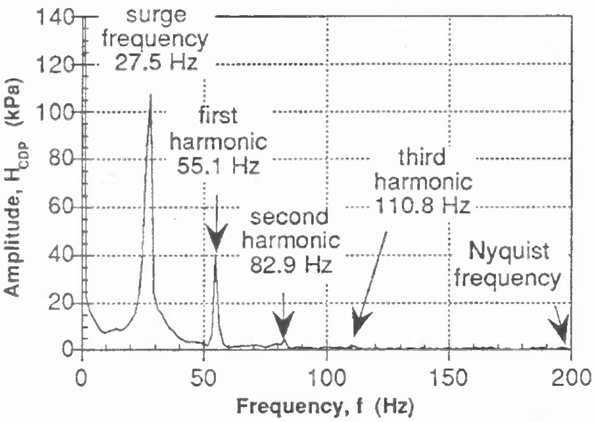

Fig. 8 FFT spectra of the periodic character of CDP during engine surge for a Williams engine

3.1.3 Williams International engine

The surge events reported for this engine were obtained at full power with a high compressor speed of about 62,000 rpm (1030 Hz) and at part power with a high compressor speed of about 55,000 rpm (915 Hz). The estimated frequency response of the on-board instrumentation was such that the data were sampled at 400 Hz. Figure 7 presents a typical CDP time history obtained during surge for the Williams engine. As shown in the figure, the general characteristics of the CDP history are consistent with the observations made for the previous two engines. In this example, the engine eventually achieves sustained operation at the initial condition. This is consistent with the results of the bore scope inspection which suggested that the engine was not so severely damaged that the control system could not recover. However, with continued exposure to the particulate environment, it became necessary to reduce the power setting to recover. The amplitude of the periodic surge/recovery cycle is substantially larger by comparison to that of the other two engines.

The periodic character of the CDP history is also shown in Fig. 7. For the FFT window shown, there were 18 surge/recovery cycles which averaged a peak-to-peak frequency of approximately 27.5 Hz. The resulting spectra from the FFT analysis is presented in Fig. 8. The first peak is located at 27.5 Hz in excellent agreement with the average peak-to-peak surge frequency observed in the time domain. The next peak is located at 55.1 Hz, the first harmonic frequency. Two very much reduced peaks can be seen at 82.9 Hz and at 110.8 Hz, corresponding to the second and third harmonic frequencies.

3.2 Observations prior to engine surge

Sample data are presented in this section for each of the three engines for the time period preceding surge.

3.2.1 Pratt and Whitney engine

A typical burner pressure history prior to engine surge was presented in Fig. 1 for the Pratt and Whitney engine. A Fast Fourier Transform (FFT) analysis was applied to the burner pressure (and also the compressor discharge pressure) history to determine whether or not a signature exists in the frequency domain which may not be evident in the time domain. The data were acquired in continuous mode enabling a comparison to be made between data well ahead of surge onset and those immediately prior to surge. The data were analyzed over an ~5 sec time interval just prior to engine surge (interval A) and compared to data in a similar time interval ~40 sec prior to engine surge (interval B). A sample of the comparison of FFT's over these time intervals is presented in Fig. 9. As can be seen there are no significant differences in the frequency spectra. It was concluded the instrumentation currently installed on this engine would not provide a precursor signal for incipient surge.

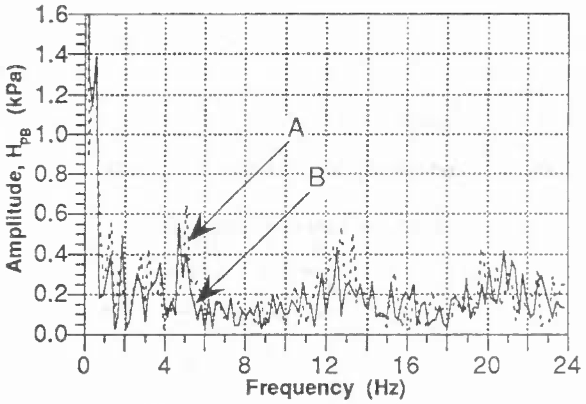

Fig. 9 Comparison of the FFT analysis of a typical PB history for time intervals prior to and distant from surge for a P/W engine

3.2.2 General Electric engine

Figure 10 shows a CDP and a pyrometer temperature time history prior to and during surge for the General Electric engine. The pyrometer senses an abrupt increase approximately 35 milliseconds prior to the time that the pressure transducer begins to decrease rapidly. Review of the video data confirmed that the pyrometer signal increase corresponds to a fireball exiting the tailpipe as was previously discussed. The frequency response of the pressure measurement system is felt to be responsible for the delay between the events in the respective data histories of Fig. 10.

A FFT analysis was performed on the pre-surge portion of both the CDP and the pyrometer time histories shown in Fig. 10. Similar to what was found for the Pratt and Whitney engine, the

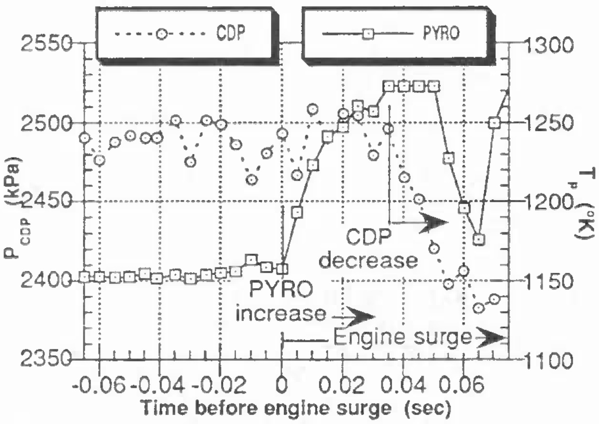

Fig. 10 Typical compressor discharge pressure and pyrometer temperature traces for a GE engine

results in the spectral domain suggested that the existing engine instrumentation was not useful for providing an indication of incipient surge.

3.2.3 Williams International engine

For the Williams International engine, a multiple surge condition is shown in Fig. 11. Note that the surge/recovery data shown on Fig. 11 has some of the characteristics of the data shown on Fig. 3 for the General Electric engine. Two distinct multiple surge events are displayed in Fig. 11. Surge was characterized by many cycles of pressure decrease and recovery. During the initial portion of the cycle, the pressure is reduced to nearly half the pre-surge value. The engine has surged once (not shown) prior to the data displayed in Fig. 11 which is why the engine is initially recovering a stable operating point.

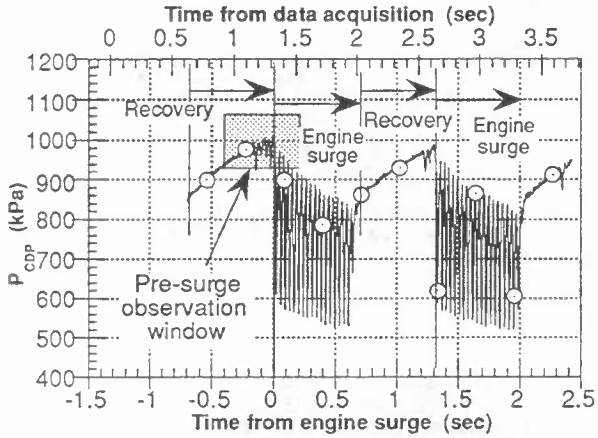

Fig. 11 Typical compressor discharge pressure history illustrating a surge for a Williams engine

Prior to the second and third series of surges shown on this figure there were several pressure excursions which were similar in character to the large pressure excursions experienced during surge, but of much smaller magnitude. The details of these excursions are clearly seen a close-up view of the pre-surge observation window presented in Fig. 12. These signals provide a precursor evident in the time domain approximately 0.15 seconds before engine surge. This time period is felt to be sufficient to initiate corrective procedures.

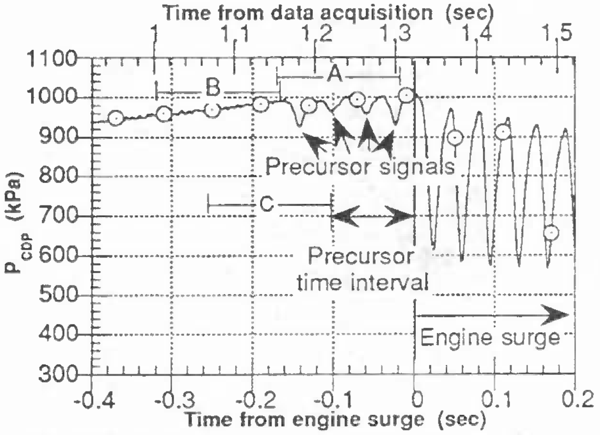

Fig. 12 Typical compressor discharge pressure precursor for a Williams engine during engine recovery

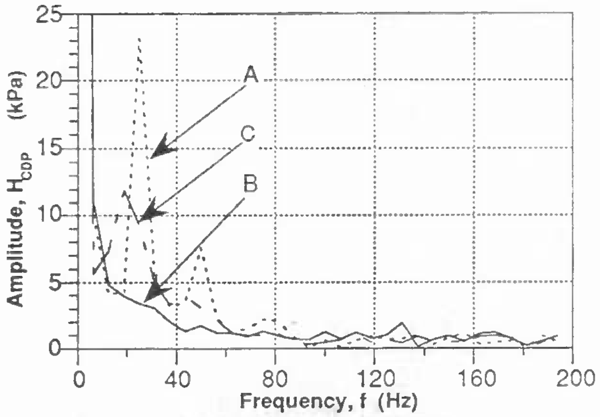

Fig. 13 Comparison of the FFT analysis of a typical CDP history using selected time intervals for a Williams engine

The first interval (A) is just prior to engine surge, interval (B) is prior to any precursors visible in the time domain, and interval (C) corresponds to a time from about 100 milliseconds prior to the small pressure oscillations to the time of surge. Figure 13 presents the comparisons of the frequency spectra. A distinct signature is present at ~25 Hz, and at ~50 Hz. The 25 Hz signature corresponds to the frequency of the surging. The signature just prior to engine surge (Fig. 12) displays the greatest perturbation in the 25-50 Hz range but leaves little warning time. In order to realize a 100 millisecond warning time, perturbations to the frequency spectra in the 25-50 Hz range on the order of those associated with interval C shown in Fig. 13 are required.

4 CONCLUSIONS

On the basis of experimental data obtained from three engines representative of those currently in the field, it was concluded that whether or not a warning of incipient surge is possible to obtain using existing on-board instrumentation is engine specific. For two of the engines studied in this work, it was not possible to obtain an early warning signal, but for the third engine it was possible to obtain a precursor approximately 100 milliseconds prior to surge. This amount of time is sufficient for the electronic control system to institute a voltage change (power point change) and thus to reduce the likelihood of surge.

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