Proceedings of the International Gas Turbine Congress 2003 Tokyo
November 2-7, 2003

IGTC 2003 Tokyo TS - 045

Experimental Investigation of Rotating Stall Inception in Axial Flow Fans

S. K. SANE[1], D. SEKHAR[2], N. V. PATIL[2], P. TAGADE[2]

[1] Professor, [2] Graduate Students , Department of Aerospace Engineering
Indian Institute of Technology Bombay, Mumbai-400 076, India
Phone: +91-22-2576-7145, Fax: +91-22-25722602 E-mail : sanesk@aero.iitb.ac.in

ABSTRACT

Opportunities created by advances in Active Control Technology for control over compression system aerodynamic instabilities have led to significant interest in the stall inception process. Serious work is being reported about full numerical simulation of this very complex phenomenon. Considering the fact that a lot depends upon the specific details of the compression system (design philosophy, blade to blade variations, tip clearance, axial gaps, solidity) it has been difficult to draw generic conclusions. Detailed experimental probing is still a must before the numerical models mature as industry standard tools. Present work attempts to capture the physics of the stall inception process. Although, the experiments are limited to a single stage low speed axial fan, care is taken to choose the design/selection of probes, sensors and data acquisition/processing tools in such a manner that these could be adopted for on-line monitoring of large compressor installations operating with aero-engines. Complex process of stall development has been captured in astonishing details with relatively simple instrumentation. Results indicate promise in the methodology chosen for real life applications. The test fan exhibits a complex three-stage progressive stall development with relatively stable intermediate stages. As exit flow is throttled down slowly, axisymmetric flow transforms into a wavy and spiky pattern of nearly one per rev frequency. This further breaks down into a multi-cell regular pattern of around two and/or three per rev frequency. Finally at very small flow rate, the instability transforms into a nearly full circumferential single cell deep stall with very complex flow pattern from hub to tip and rotates at about 35 % of rotor speed. It is interesting that traces of this feature are found all along during this development.

NOMENCLATURE / ABBREVIATIONS

ADC - Analog to Digital Converter
'B' - Greitzer's B parameter
CFD - Computational Fluid Dynamics
DC - Direct Current
DFT - Discrete Fourrier Transform
FFT - Fast Fourrier Transform
G-M - Greitzer - Moore
HTR - Hub Tip Ratio
N-L - Non - Linear
PC - Personal Computer
WG - Water Gauge
η - Static Efficiency
φ - Flow Coefficient
ψ - Pressure Rise Coefficient

Manuscript Received on March 26, 2003

INTRODUCTION

In the absence of reliable prediction and control of aerodynamic instabilities in the compressors, employed in aircraft turbine engines, designers have to sacrifice precious performance to provide adequate stall/surge margins. Significant investments have been made in recent past to understand the complex underlying physics both experimentally and through numerical simulations. Considering the real situation, as obtained in a particular installation, generic numerical tools with reliable or reasonable predictive ability are a difficult proposition and the importance of experimental route could not be overemphasized, at least for sometime. Significant experimental work has been reported in the literature and is continuing with more and more sophisticated instrumentation and signal processing techniques. Although, a lot can be learnt from detailed measurements by using laser and hot wire velocimetry, the choice of sensors and data processing must keep the final practical implementation in real life situations as against laboratory. Present paper reports the work conducted on a low speed fan to capture the stall inception process with relatively simple instrumentation. Possibility of employing similar techniques in actual flight environment was always kept in focus.

REVIEW OF LITERATURE

The main objective of the present study was to establish a reasonable test facility for some deeper probing into the stall inception process and mechanisms. Thus the focus of literature review was on past experimental research in order to ascertain the requirements for various sensors, signal conditioners, data acquisition wares, data processing and presentation formats. One other self-imposed requirement was that all the experimental techniques developed should be, in principle, usable for similar studies on an operating aero gas turbine compression system in the flight environment. In this context intrinsic real time capability is also an important issue. The author is personally aware of a few stall/surge-sensing systems on some current military aero gas turbine engines, including the definitions for 'surge signal and its threshold'. Literature review was also relevant to approximately fix the length and time scales appropriate to the present experimental set up.

Emmons (1966) reported early experimental work with externally mounted hot wire probes, fed through wall static pressure taps. Studies were made on cascades and compressor stages. Schlieren shadowgraph was employed to visualize the flow field during stall propagation.

Day (1978) employed hot wire and pressure probes to map the detailed flow structure. Data was able to quantify the radial stall extent in a multi cell structure.

Delahaye (1983) conducted experiments to detect stall /surge in full engine environment. High response static pressure probes, with a bandwidth of 10 kHz, were used in conjunction with monitoring of other engine parameters. Multi-channel cross correlation was used very effectively.

Jackson (1987) reported experiments with a 0.7 HTR low speed compressor. Hot wire probes located in axial and radial stations were used to study stall inception and development. Stall was found to be not stochastic and multiple-cell inception provided useful correlation between stall cell size and speed. It was possible to fix the inception point to a particular blade with good repeatability.

McDougall (1990) used hot wire probes both in absolute and relative frames. Effect of tip clearance (0.5-1.2-3.0 %) is significant and small clearance leads to tip stall and large tip clearance to hub stall. It is also reported that high HTR makes the rotor stall prone. Hub flow is loaded with pre-stall indicators relative to tip.

Garnier (1991) has used hot wire and wall static Kulites for low and high speed experiments. Large number of probes were used in both axial and circumferential directions to map the flow field in space and time through DFT. Small amplitude waves were noticed prior to stall. Effect of inlet distortion was similar at both the speeds.

Inoue (1991) has presented an innovative concept for stall inception as a measure of 'collapse of periodicity' of casing wall pressure fluctuations. Based on only single sensor measurement this is a very useful suggestion. Application of the suggested 'similarity coefficient' to a variety of data may be very interesting.

Day (1993, 1993) used hot wire and wall static probes to detect modal wave and spike structures prior to stall. Both these appeared near the peak of the steady state map. Active control of stall was attempted through damping of the modal waves by air injection in the vicinity of stall cells. Method reportedly worked for surge as well.

Lawless (1994) rightly objects the use of hot wire probe and uses small microphones quite innovatively. Their utility is established by comparison with hot wire probes. Large number of these microphones were positioned at axial and circumferential stations to resolve the physics both spatially and temporally. Stall inception assessment was not very conclusive.

Kim (1994) worked on same facility as Lawless (1994) but used variety of cross-hot wires and miniature wall pressure probes on the blade surface. Data was acquired at 5 kHz and band passed for 0.5-100 Hz. The efficacy of 'B' parameter was demonstrated.

Hoying (1995) has reported work on 4-stage high-speed core compressor and has used wall static pressure probes. Through spatial FFT modal waves were discerned 100-200 revs prior to stall. Interestingly the method seems to work for operation with inlet distortion as well.

Blanco (1996), employed rotating hot wires in addition to static hot wires to establish stall inception by comparison of the two. Data was sampled at 8 kHz and filtered up to 1 kHz. Large numbers of radial and circumferential stations were used to map the detailed flow field. The suggested mechanism of stall inception is through 'tip blockage'.

Poensgen (1996) has presented data regarding a single stage compressor indicating modal wave inception into a single cell stall and its progression into a two cell split. Present author has also witnessed similar stable transition, in case of a large three stage transonic compressor operating at low speeds, near idle. Use has been made of unsteady total pressure probes, triple hot wires and a single hot wire to obtain detailed flow structure inside a stall cell. Comparison with G-M model is presented, indicating usefulness of such simple tools as against full CFD.

Hendricks (1997) reports experiments with 11- stage variable geometry core compressor by using circumferentially spaced total/static pressure probes at various axial stations. The FFT analysis of data suggests presence of rotating stall before surge.

Freeman (1998) presents experiment with Viper engine compressor. Data of circumferentially located Kulites at 4 kHz was useful in identifying various mechanisms of stall inception and their correlation with other engine parameters. Active control strategy has been demonstrated.

Camp (1998) reports results of spatial Fourier analysis of six circumferentially positioned hot wire probes. For positive incidences spike activity was noticed near tip section. It has been found that near the peak of steady state map, modal waves appear and lead to spikes at particular blade(s) near hub. Both these precursors can occur simultaneously and depend upon the incidence and peak pressure growth.

Hoying (1999) reports numerical assessment of earlier experiments of Hoying (1995), indicating forward tip vortex movement prior to stall, resulting in short scale spikes.

Saxer (1999) reports a parallel numerical and experimental study of rotating stall. Water model of a 4-stage compressor is instrumented with flow visualization and wall static pressures. Spike type inception jumps into a single cell stall before further progressing into axi-symmetric fully stalled flow.

Bright (1999) has reported a very interesting technique of using one single sensor for detection of instability by correlating a non-linear statistic 'correlation integral' to instability frequencies.

Inoue (2000) has used a single slanted hot wire and a five-hole pressure probe traverse at various axial stations. In addition 14 wall static pressure data has been collected. The data is analyzed with FFT/Wavelet tools and suggests a complex transition from single to multiple cell structures leading finally to single cell deep stall. Stall speeds vary from 72 to 29 % rotor speed during this transition.

Inoue (2001) is an excellent review of compressor instabilities and has been a very useful bibliographic aid. Initial high frequency instability may not degrade the performance and may not be noticed at all but has serious mechanical ramifications. A very interesting picture of multiple part-span cells, tornado tip vortices and tip leakage vortex has been presented. Comparison with numerical results is indicative of the power of CFD tools, if used judiciously.

Wagner (2001) has reported effect of inlet distortion by employing an array of hot wire, wall static pressure and one-hole dynamic pressure sensors. Active control capability with an N-L observer based controller has been experimentally verified.

Gogoi (2002), in association with present authors, has indicated a possible simple numerical simulation of the stall inception and development process.

Thus, based on the above literature review and experience of the author in earlier experiments, it may be a good strategy to employ static and dynamic miniature pressure probes at few stations to identify the instability inception point and its growth. Data collected is meaningful only if it can be presented properly and understood.

EXPERIMENTAL RIG

Experimental Rig was assembled around a low speed single stage upstream stator fan, specially designed and built for this purpose. Both rotor and stator blade solidities and stagger were adjusted to get reasonable stall characteristics. The details of the fan design are given in Table. 1. The values given in parenthesis for φ and ψ are design intents.

Table 1 Fan Design parameters

Parameter	Values
Tip Diameter, D_t	394, mm
Hub diameter, D_h	265, mm
Rotor speed, N	2400, rpm
Max. Flow coefficient, φ	1.0 (1.4)
Max. Pressure coefficient, ψ	0.55 (0.59)
Haller number, V_2/V_1	0.9
Rotor blade camber angle	15^o
Rotor stagger angle, ξ_R	35.65^o
Rotor blade profile	F-series
Solidity of rotor blades, c/s	0.96
Stator stagger angle, ξ_S	10.5^o
Stator blade profile	F-series
Stator blade camber angle	21^o
Stator blade, solidity c/s	1.08

A schematic of the rig is shown on Fig. 1. 60^o cone bell mouth feeds the ambient air via an inlet duct into the bullet nose faced stator wheel and on to the rotor. The drive is hub mounted and the air is exhausted via an exit duct and a movable cone throttle.

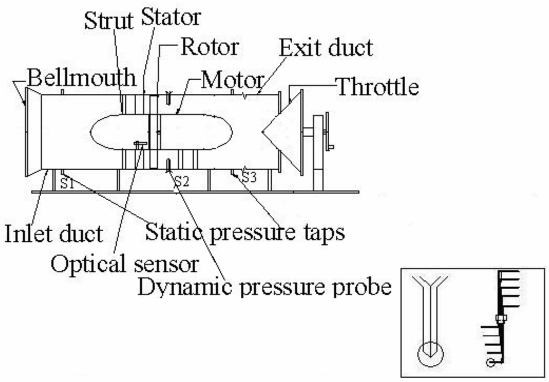

Fig. 1 Experimental setup

The volume flow rate is measured through six wall- static pressure taps, equally spaced circumferentially at quarter bell mouth diameter. The static pressure rise, likewise, is measured between stations s1 and s3. Dynamic pressure probes, as shown on inset on Fig. 1, are positioned at station s2. Similar probe is being used in surge sensing unit in some operating military engines. A five-probe dynamic pressure rake (see inset on Fig. 1) is also positioned before and after the rotor wheel. The rake-probe tips are aligned with the blade span and in axial direction. Differential pressures are monitored through a set of $\pm$ 2.5, $\pm$ 5 and 0-10 inches WG strain gauge sensors with typical response time of 1 ms. A proximity optical probe gives 1 per revolution reference pulse and a proximity capacitance probe gives reference pulse for every blade and also monitors the tip clearance. All the signals are logged in the 0-10 V range by a 12-bit, 8-channel ADC AD574 with a sampling time of around 40 μs per channel. This gives an overall minimum sampling time of 400 μs or more, which is enough to capture the blade passing frequency (720 Hz). Data is logged through dedicated software on to a PC for further analysis. The exact sampling time for each channel is also logged for accurate phase diagnosis. All pressure sensors were static calibrated and connecting tubing was checked for possible resonance interference. Each individual ADC channel was calibrated for scale and offset factors. The acquired time histories were analyzed through standard DFT software with/without Windowing and sliding time window. The input power to the rotor was monitored through the calibrated DC motor drive.

RESULTS AND DISCUSSION

Steady State Characteristics:

The exit cone was slowly moved in from its fully open position to almost fully closed and data was recorded at large number of points under steady state as defined by constant drive speed (2400 rpm) and fixed exit cone position. The data, thus obtained, was reduced in standard dimensionless form (ψ, η = f(φ)) and is shown on Fig. 2.

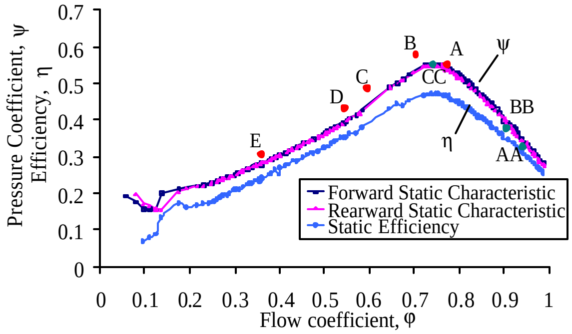

Fig. 2 Steady State Characteristics

Points, labeled by letters AA-CC and A-E, indicate initiation of a particular instability, unsteadiness or non-uniformity as the case may be. These have been discussed below with reference to amplitude-frequency-time-histories of the signals. As can be seen from Fig. 2, there is no abrupt stall nor there is any appreciable hysteresis.

Data Reduction and Presentation:

The 'dynamic pressure' probe in fact reads the difference between the total pressure and the base pressure, which is somewhat higher than the dynamic pressure. The ADC count is post multiplied by sensor calibration to indicate the result in Pa. Data was recorded for a five second event with small throttle movement in between. Several such files were collected in quick succession while ensuring that speed is maintained constant at 2400 rpm.

Fig. 3 to Fig. 13 show maximum of seven time traces and is indicative of the efficacy of simple instrumentation employed. The data presented are small excerpts from a 5 second data file (10000 points for each of the seven channels sampled at 500 µs) showing up a few rotor revolutions of interest.

Development of Progressive Stall:

The flow in the hub and tip regions of the test fan is appreciably unsteady even under the stable operating conditions, as indicated by the negatively sloped curve on Fig.2, up to point A. As indicated on Fig. 3, even at point AA (φ = 0.94, ψ = 0.325) there is considerable activity at both hub and tip. The tip flow is in forward direction and multiple cells are formed with a tendency to merge into a single cell. In contrast, at hub there is a lot of single cell unsteadiness. Some spiky nature can even be seen at tip-mean station as well.

As the exit throttle is closed up to point BB (φ = 0.905, ψ = 0.379), as seen on Fig. 4, the tip flow is significantly reduced with increase in multi-cell activity. There is increased activity at hub and there is an overall flow adjustment in the sense that the reduction in flow at hub leads to increased flow at all other radial stations, except tip.

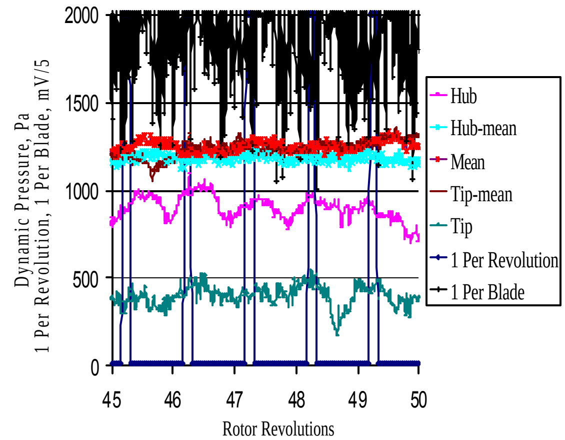

Fig. 3 Time History at 'AA'

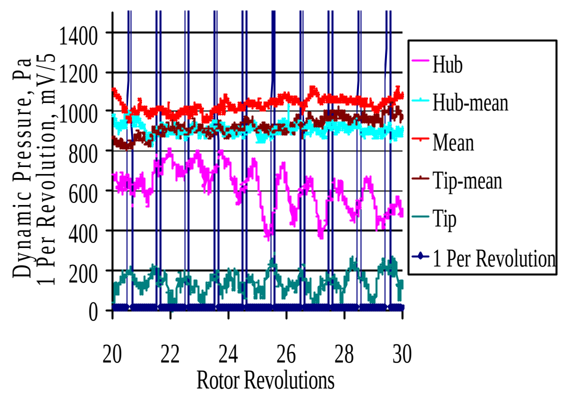

Fig. 4 Time History at 'BB'

As the throttle is further closed, as at points CC (φ = 0.742, ψ = 0.551), the unsteady flow further develops as shown on Fig. 5. The tip flow is substantially reduced with flow reversal and a very strong single cell activity at hub.

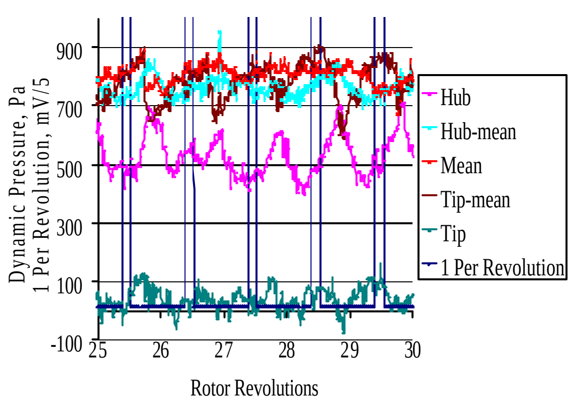

Fig. 5 Time History at 'CC'

The flow at all other stations is now showing both short scale spikes riding over nearly full circumferential single cells. A similar picture is seen on Fig. 6 for point ‘A’ (φ = 0.774, ψ = 0.552). Experimental points AA to CC and A to E were obtained through two independent experiments.

The tip region is operating at very small velocities with some negative velocity spikes. The hub region has a well defined nearly one per revolution modal wave with appreciable amplitude. The three main traces covering bulk of the annulus have reasonably same mean velocity. The modal wave and spikes could be seen in all three but more markedly in the tip-mean region, with multiple cell initiation.

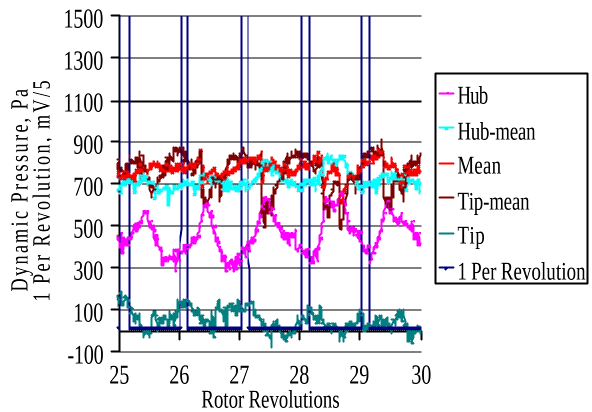

Fig. 6 Time-History at 'A'

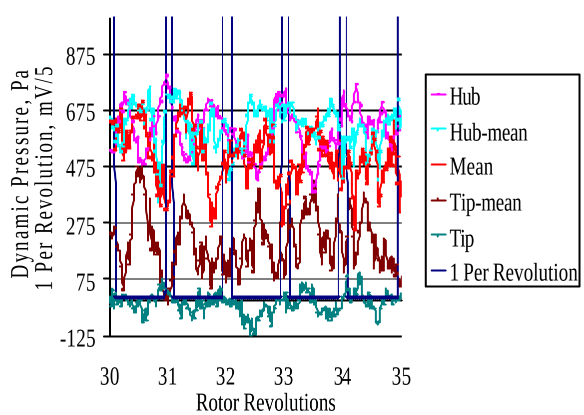

Fig. 7 Time-History at 'B'

At point ‘B’ (φ = 0.703, ψ = 0.578), as seen on Fig. 7, the stalled region has spread up to tip-mean station with multiple cells. The tip reversed flow has been strengthened but still with multiple cell structure. The average velocities from mean to hub is nearly same (at reduced level) and similar multiple cell structure could be seen with much stronger activity at mean station.

At point ‘C’ (φ = 0.596, ψ = 0.488), as seen on Fig. 8, the stall has further grown span wise and even at tip-mean region, there is some flow reversal. Although, the multiple cell character has been retained the hub shows large jet like flow with very high velocity.

Further, as we close the exit throttle, the operating point shifts to ‘D’ (φ = 0.545, ψ = 0.433), as shown in Fig. 9. Here the flow seems to reorganize itself into a two-cell structure in large part of the entire span.

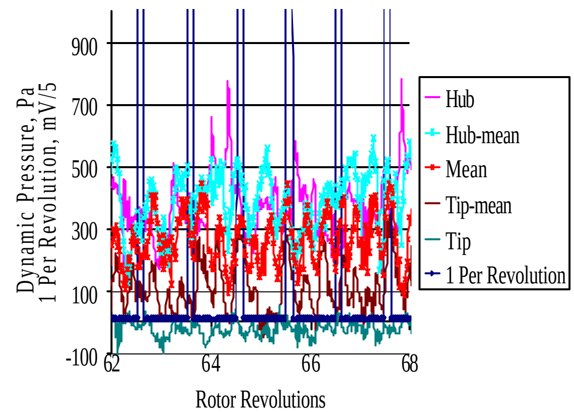

Fig. 8 Time-History at ‘C’

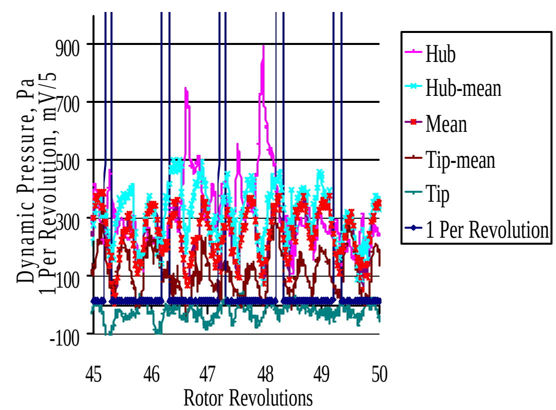

Fig. 9 Time-History at ‘D’

The high velocity jets at hub continue to appear from time to time before it merges with the rest of the flow, now at substantially low flow coefficient (0.545). The two cell structure is generally seen everywhere.

As the flow is reduced further, as at point ‘E’ (φ = 0.360, ψ = 0.306), the multiple cell stall transforms into a full circumferential deep stall as seen in Fig. 10. Fig. 10 presents a very complex flow picture as all the signals are overlapped due to poor time resolution. Fig. 11 and Fig. 12 show successive close-ups of the single cell deep stall, which rotates at (14/40 Hz) 35 % of rotor speed. Flow reversal could be seen in the entire span with high velocity forward flow. Particularly, the hub flow transforms into very high velocity jet like streams from time to time. These jet-like structures seem to appear in every alternate cycle of the deep stall, indicating very complex span wise flow convection/redistribution.

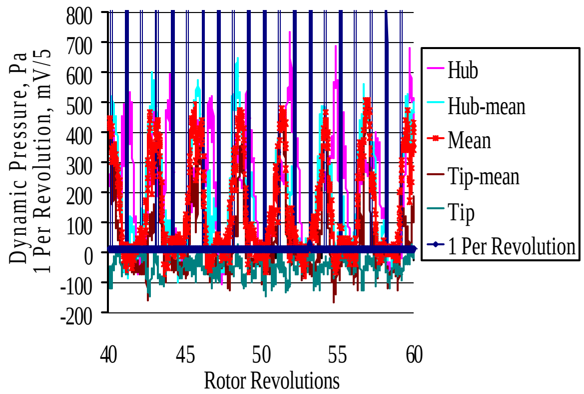

Fig. 10 Time - History at 'E'

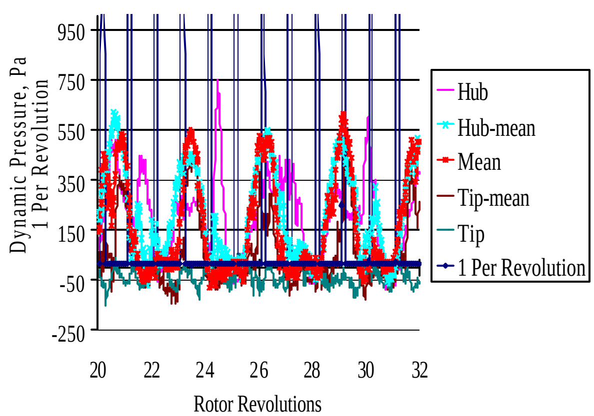

Fig. 11 Time History at 'E', Close-up

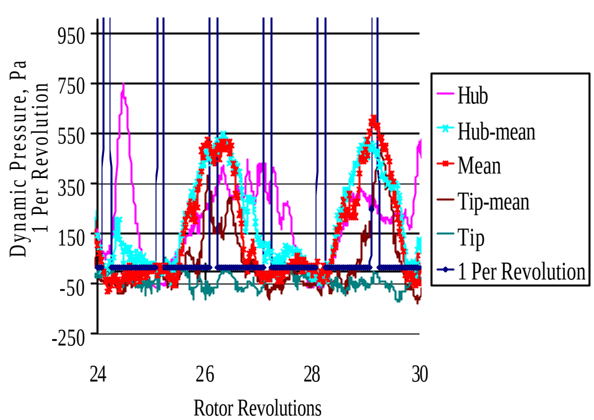

Fig. 12 Time History at 'E', Close-up

DFT Analysis Presentation:

The entire 10000 point data captured for 'mean' station was subjected to 2000 point DFT with sliding time window by 200 samples or 0.1 s. There were a total of 12 such files recorded in quick succession. All components with amplitude greater than 4 % of DC were noted down in time as the operating point shifts from 'A' to 'E' on the Map as on Fig. 2. This makes a very interesting presentation as shown on Fig. 13.

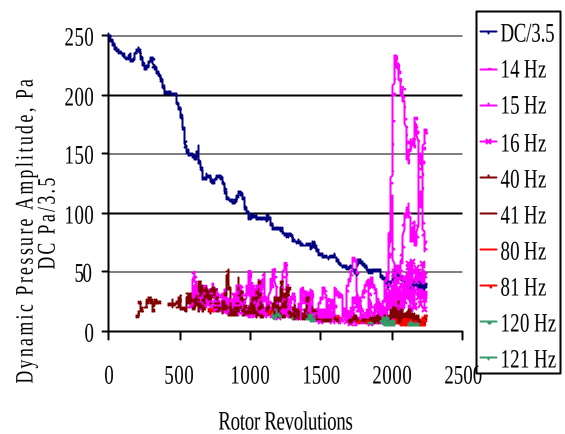

Fig. 13 Amplitude – Time History (mean)
(Fluctuating Components > 4 % DC)

As can be seen from Fig. 13, the instability at mean station begins as weak modal waves of frequency almost equal to rotor. The main deep stall frequency of 14 Hz is present in weak form for a long time but picks up rapidly towards the end, when its amplitude is much larger than the DC itself. Higher modes seem to appear intermittently but all are present in the end in some measure. DC component (time average) has to decrease with throttling, but the waviness is, perhaps, associated with the manual speed control. Similar analysis can be done for the remaining four radial stations.

CONCLUSIONS

General

It may be mentioned that present experimental work was motivated by a requirement to establish a rotating stall demonstration rig for routine pedagogic needs. Some deficiencies have been noticed in the course of the present work and the flow path needs some aerodynamic cleaning. Rotor tip clearance has to be controlled more closely by providing a concentric casing liner. The exit hub needs to be provided with smooth area variation through a reverse cone. The drive speed needs to be controlled automatically. Nonetheless, following observations can be made at this stage.

The probes, sensors and data acquisition system adopted in the present work have proved their capability by very ably capturing the detailed physics of the stall inception process and can be used for similar experiments on real life engine installation with suitable revision of specifications. The present design exhibits a very gradual progressive stall.

The disturbance noticed particularly at Hub and Tip sections, even well before the peak of the steady state characteristics, is somewhat unusual. This 'Instability' in the apparent 'Stable' zone is well defined as modal waves with frequency very close to the rotor speed. The only explanation for this observation is that these disturbances may be arising due to large eccentricities between rotor hub and tip circles relative to the respective stator hub and casing circles. The rotor has been machined but casing and stator hub are formed from sheet metal. In addition to the above, following conclusions can be made:

The instability begins as modal oscillations, rotating at speeds almost close to rotor speed, and transforms into spiky multi-cell structures. The process starts at hub but spreads to other radial stations in a similar manner.

Further decrease in flow coefficient leads to stall splitting and a two-cell structure is obtained at almost all stations, rotating thus at same speed as rotor. Three or more cells were also observed intermittently.

As the flow is reduced further the instability transforms as a single full circumferential deep stall, rotating at 35 % of rotor speed, with a very complex flow structure.

Under the conditions of deep stall the hub flow shows very high velocity jet like structure, covering about 1/2 circumference, when all other stations are fully stalled. This pattern is followed by a pattern, where all radial stations, except tip, have almost identical flow structure. The above sequence of two flow patterns seems to repeat itself.

Detailed Stall Inception Process

As mentioned earlier, Fig. 3 to Fig. 13 present only a small portion of the data collected at the six points AA, BB, CC, A, B and C, as shown on Fig. 2. At each point data for all seven channels was collected at 2 kHz for a duration of 5 seconds. Perusal of this complete information suggests following sequence of growth of the instability, as summarized in the table below:

Point	Average Dynamic Pressure, Pa, at					Comment
	H	H-M	M	M-T	T	
AA	1000	1250	1250	1250	500	1
BB	700	1000	1000	1000	125	2
CC-A	500	700	800	800	+ 0 -50	3
B	650	650	500	250	- 0	4
C	250	250	250	250	- 50	5

Comments:

1. As per the table above, at AA the three middle sections have large flow velocities, hub section has 25% less and tip section has lowest value, which is 250% less. Even at this point small intermittent oscillations could be seen at hub and tip sections.
2. At point BB, the velocity at the tip section drops drastically with lesser drops at other stations. The oscillations at both hub and tip are now more pronounced and at almost 1 per rev frequency. This suggests the presence of modal waves.
3. At points CC or A, the tip flow is reduced to very small but positive values. The flow at other stations is also reduced but the flow pattern is similar. The oscillations at both hub and tip sections have grown further and spread now to adjacent sections in both the directions. The mean shows intermittent spiky flow, which was also present at other stations earlier, but much less pronounced.
4. At point B, the tip flow reversal is noticed from time to time with almost zero average. There is a reorganization of the flow with higher flow at hub and hub-mean sections. The flow at tip-mean and mean sections has dropped considerably. There are large oscillations present in all the stations with mean station flow indicating spiky behavior.
5. At point C, the fan is fully stalled with flow reversal in all the sections, covering a large segment of the circumference. The flow structure suggests a two cell unsymmetrical pattern. The first cell is present in all sections, except tip, where the average flow is zero. The second cell is present in hub and hub-mean sections only with zero or reversed flow at all other sections.

Thus, in conclusion, it can be said that the instability begins as pronounced modal oscillations at 1 per rev frequency with intermittent spiky nature of the flow. The inception starts at a point before the pressure rise peak (a point in between BB and CC) and this could be used to define stall margin. The instability grows immediately after peak of pressure rise (point B). The initial two cell structure may be due to rather large rotor solidity.

ACKNOWLEDGEMENTS

The authors are grateful to several faculty colleagues of the Departments of Aerospace and Electrical Engineering for intense discussion and useful suggestions. The authors are thankful to technical staff and students for valuable help during the conduct of experiments.

BIBLIOGRAPHIC REFERENCES

Blanco-Marigorta, E., et al, 1996, "Hot Wire Measurements during Rotating Stall in a Variable Pitch Axial Flow Fan", ASME, 96-GT-441.

Bright, M. M., et al., 1999, "Investigation of Pre-Stall Mode and Pip Inception in High Speed Compressors through the Use of Correlation Integral", ASME, Journal of Turbomachinery, Vol. 121,Oct. 1999, pp- 743-749.

Camp, T. R., Day, I. J., 1998, "A Study of Spike and Modal Stall Phenomenoa in a Low-Speed Axial Compressor", ASME, Journal of Turbomachinery, Vol. 120, July 1998, pp-393-401.

Day, I. J., Cumpsty, N. A., 1978, "The Measurement and Interpretation of Flow within Rotating Stall Cells in Axial Compressors", ImechE, Journal of Mechanical Engineering Science, Vol. 20, No. 2, pp- 101-115.

Day, I. J., 1993, "Stall Inception in Axial Flow Compressors", ASME, Journal of Turbo-machinery, Vol. 115, Jan 1993, pp- 1-9.

Day, I. J., 1993, "Active Suppression of Rotating Stall and Surge in Axial Compressors", ASME, Journal of Turbo- machinery, Vol. 115, Jan 1993, pp- 40-47.

Delahaye, B., 1983, "Study of Instabilities in Axial Flow Compressrs", ISOABE, 83-7076, pp- 656-664.

Emmons, H. W., et al., 1966, "Compressor Surge and Stall Propogation", Transactions of the ASME, May 1966, pp- 455-469.

Freeman, C., et al., 1998, "Experiments in Active Control of Stall on an Aeroengine Gas Turbine", ASME, Journal of Turbomachinery, Vol. 120, Oct. 1998, pp- 637-647.

Garnier, V. H., et al., 1991, "Rotating Waves as a Stall Inception Indication in Axial Compressors", ASME, Journal of Turbomachinery, Vol. 113, April 1991, pp- 290-302.

Gogoi, A., et al., 2002, "A Model for Rotating Stall and Surge in Axial Flow Compressors", AIAA 2002-4086

Hendricks, G. J., et al., 1997, "Analysis of Instability Inception in High-Speed Multistage Axial Flow Compressors", ASME, Journal of Turbomachinery, Vol. 119, Oct 1997, pp- 714-722.

Hoying, D. A., 1995, "Stall Inception in a Multistage High Speed Axial Compressor", Journal of Propulsion and Power, Vol. 11, No. 5, pp- 915-922.

Hoying, D. A., et al., 1999, "Role of Blade Passage Flow Structures in Axial Compressor Stall Inception", ASME, Journal of Turbomachinery, Vol. 121, Oct. 1999, pp- 735-742.

Inoue, M. et al., 1991, "Detection of a Rotating Stall Precursor in Isolated Axial Compressor Rotor", ASME, Journal of Turbomachinery, Vol. 113, April 1991, pp- 281-289.

Inoue, M. et al., 2000, "Propagation of Multiple Short-Length-Scale Stall Cells in an Axial Compressor Rotor", ASME Journal of Turbo- machinery, Vol. 122, pp. 45-54.

Inoue, M., 2001, "High-frequency rotating instab- ilities in axial flow compressors", *Proceedings of International Symposium on Air breathing Engines*, Bangalore, ISABE-2001-1008.

Jackson, A. D., 1987, "Stall Cell Development in an Axial Compressor", ASME, Journal of Turbomachinery, Vol. 109, Oct 1987, pp- 492-498.

Lawless, P. B., et al., 1994, "Characterization of Abrupt Rotating Stall Initiation in an Axial Flow Compressor", Journal of Propulsion and Power, Vol. 10, No. 5, pp- 709-715.

Kim, K. H., Fleeter, S., 1994, "Compressor Unsteady Aerodynamic Response to Rotating Stall and Surge Excitations", Journal of Propulsion and Power, Vol. 10, No. 5, pp- 698-708.

McDougall, N. M., et al., 1990, " Stall Inception in Axial Compressors", ASME, Journal of Turbo-machinery, Vol. 112, Jan 1990, pp- 116-125.

Poensgen, C. A., Gallus, H. E., 1996, "Rotating Stall in a Single-Stage Axial Flow Compressor", ASME, Journal of Turbomachinery, Vol. 118, April 1996, pp- 189-196.

Saxer-Felici, H. M., et al., 1999, "Prediction and Measurement of Rotating Stall Cells in an Axial Compressor", ASME, Journal of Turbomachinery, Vol. 121, April 1999, pp- 365-375.

Wagner, S., Hennecke, D. K., 2001, "Observer Based Active Stall Avoidance for an Axial Compressor Stage with Inlet Distortion", *Proceedings of International Symposium on Air breathing Engines*, Bangalore, ISABE - 2001 - 1162.