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Spike-Type Compressor Stall Inception, Detection, and Control

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fluid dynamic instability, gas turbine, flow control, fluid machinery

Abstract

An aerodynamic instability known as stall occurs in axial compressors as the mass flow rate is reduced and the blade loading reaches its limit. At this limiting condition, an easily recognizable flow breakdown process, known as spike-type stall inception, is observed in most modern compressors. This article begins by examining measurements from both low- and high-speed compressors to explain the characteristic features of spike-type stall. This is followed by a review of past work on compressor stability and an assessment of recent advances in this field. Included here is a study of the three-dimensional flow features that typify spike formation and its eventual growth into a mature stall cell. We also consider the formation criteria for spike-type stall and the means for early detection and possible control. On the computational side, a possible mechanism for spike formation is identified from three-dimensional studies of the flow in the rotor tip region. This mechanism involves tip-clearance backflow at the blade's trailing edge in combination with forward spillage of tip-leakage flow at the leading edge. This flow pattern implies that a successful stall-control technology will have to rely on an effective means of suppressing tip-clearance backflow and forward spillage.

1. INTRODUCTION

Compressor characteristic: graphical description of the compressor performance made up of the overall pressure rise across the compressor versus the mass flow through it

Compressor operating range: quantitative measure of the mass flow range over which stable operation is possible, i.e., operation without choking, stalling, or surging

The pressure rise delivered by an axial compressor is usually defined as the ratio of the exit stagnation pressure to the inlet stagnation pressure. This ratio can be plotted as a function of the mass flow rate (for a given shaft speed) to produce a fixed-speed performance curve, or characteristic curve. A compressor map, covering the full operating range of the machine, from low to high speed, consists of a set of performance curves, each corresponding to a specific rotational speed. A typical example is shown in **Figure 1**. All compressors are required to operate over a range of speeds and mass flow rates with acceptable efficiency and stability margin (Cumpsty 2004). The stability margin at any particular speed is defined as the safe operating range between the design flow rate and the lowest flow rate at which stable operation can be maintained. At low mass flow rates, a stability limit is reached, which is usually demarcated as the stall/surge line on the compressor map (**Figure 1**). In most cases, the aerodynamic instability that sets in at low flow rates, i.e., rotating stall, grows out of a small, localized, disturbance in the process referred to as spike-type stall inception.

Most instabilities in axial compressors manifest themselves as wavelike disturbances propagating around the compressor annulus in the circumferential direction with an (angular) phase speed ranging from approximately 20% of the rotor rotational speed to a value larger than the rotor speed. The wavelength of these disturbances ranges from the full compressor circumference down to one or two blade pitches (one blade pitch is the spacing between two adjacent blades in a blade row). Typically a compressor blade row has 20 to over 80 blades so that the wavelengths can differ by an order of magnitude. The phase velocity and the wavelength of the disturbances are set (in a process as yet not fully understood on a quantitative basis; see Section 4 below) by the compressor's design characteristics and geometric details, which can vary widely from compressor to compressor.

At the instability inception stage, the amplitude of these wavelike disturbances is generally small relative to the mean velocity through the compressor, but grows in magnitude as the instability evolves toward its final state. The final state of the instability consists of localized stall cells, which are regions of low velocity often with reversed flows covering a sector, or multiple sectors, of the compressor annulus (i.e., single or multiple stall cells). These stall cells propagate with a

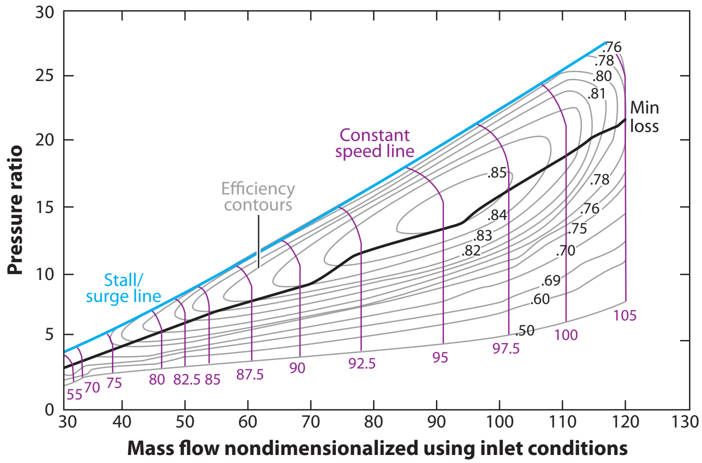


Figure 1

A representative compressor map showing the working line (minimum loss line) and the rotating stall/surge line at low flow rates that limit the compressor's useful operating range. Figure used with permission from General Electric Aviation.

circumferential phase velocity of between 20% and 80% of the compressor's rotational speed. In this state, the compressor is referred to as operating in rotating stall (Day 1976) and has reduced mass flow and pressure ratio. The operating point is in fact off the normal compressor performance map. Depending on the pumping system in which the compressor operates, it may undergo a second type of instability, which is termed surge. Surge is essentially a one-dimensional (axisymmetric) system instability that involves an overall oscillation in annulus-averaged flow (Emmons et al. 1955; Greitzer 1976, 1981). In most cases (except at very high rotational speeds, or very high pressure ratios), surge is preceded by, if not triggered by, rotating stall.

In the initial stages when the instability is linear, surge is often described as a zeroth-order instability mode, i.e., a growing planar wave propagating in the axial direction. In the same way, the circumferentially propagating wave disturbance that eventually develops into rotating stall can be described as a higher-order mode (i.e., a wave disturbance with circumferential harmonics of one and higher) (Chue et al. 1989, Moore 1984, Moore & Greitzer 1986, Paduano et al. 2001).

Stagnation-to-static pressure rise characteristic: compressor performance characteristic expressed in terms of the difference between the stagnation pressure at the inlet and the static pressure rise at the exit

For these circumferentially propagating waves, which are associated with the onset of rotating stall, there are two generally recognized stall-inception types, each with its own distinctive characteristics (Camp & Day 1998; Day 1993a,b; Day & Freeman 1994; Escuret & Garnier 1996). The first type of inception, referred to as modal-stall inception, is characterized by the growth of small-amplitude, two-dimensional, long-length-scale (approximately equal to the compressor circumference, π multiplied by the compressor diameter) wavelike disturbances extending axially through the compressor. These disturbances, referred to as modes, can often be detected tens or hundreds of rotor revolutions prior to stall onset and propagate in the circumferential direction at speeds ranging from 20% to 50% of the rotor speed (Haynes et al. 1994, McDougall et al. 1990, Tryfonidis et al. 1995). In general, modal-type stall inception is observed to occur when the stagnation-to-static pressure rise characteristic of the compressor has a zero slope (i.e., at peak pressure rise). Paduano et al. (2001) provide a review of modal-type stall inception.

The second type of stall inception, referred to as spike-type inception (the topic of this review), is characterized by the formation of three-dimensional, finite-amplitude disturbances (after Day 1993b) localized to the tip region of just one rotor row in a multistage compressor. As described in Section 2 below, spike-type stall inception is distinctly different from modal-stall inception in both timescale and length scale. (The term spike has come into common usage because any pressure measurement taken upstream of a developing disturbance will show an upward spike. Measurements of velocity, conversely, will show a downward spike.)

The distinct differences in the timescale and length scale of the two types of stall inception have strong implications for their modeling, their measurement, and their management (in terms of active or passive control). The general topic of modal-stall inception and active control has been discussed by Paduano et al. (2001). The purpose of this review is to describe the improvements in understanding that have taken place since the discovery of spikes by Day (1993b). We discuss the characteristic behavior of spikes, investigate the likely fluid mechanisms responsible for this type of stall inception, and summarize recent trends in spike modeling, detection, and control.

2. BACKGROUND: COMPRESSOR SPIKE-STALL INCEPTION

The recent attempts to control instability phenomena in axial compressors have pointed to the importance of understanding the underlying fluid dynamics of the stall-inception process. In this section, we examine the experimental data from compressor and engine test rigs to elucidate the flow features that characterize spike-type stall inception. The experimental observations provide the background and basis for (*a*) attempts to detect precursory signs of spike formation, (*b*) the use of computational fluid dynamics (CFD) to extract the physical processes responsible for spike formation, (*c*) the analytical/computational requirements necessary to analyze and predict spike formation, and (*d*) the prospects for controlling or delaying stall onset.

2.1. Experimental Observations on Spike-Stall Inception

As stated in Section 1, the most common route to rotating stall in axial compressors is via a spike-type inception process that involves the growth of localized nonlinear short-wavelength disturbances. Substantial experimental evidence has shown the prevalence of this type of stall inception; examples include the work of Day and coworkers as noted above and more recently reports by Deppe et al. (2005), Bennington et al. (2007), and Spakovszky & Roduner (2007) (in centrifugal compressors). **Figure 2*a*** shows a typical set of circumferentially spaced velocity traces during a stalling event. The inception process starts with a spike-shaped disturbance, at approximately revolution 15 in the figure, which grows in size as it rotates around the annulus and turns into a fully developed stall cell within approximately five rotor revolutions. The circumferential phase speed with which the emerging cell moves around the annulus changes from an initial value of 72% of the rotor speed when the cell is small to approximately 40% of the rotor speed when fully developed. A more detailed velocity trace of a spike disturbance (Silkowski 1995) is shown in **Figure 2*b***. The spike usually has a characteristic length scale of approximately three blade pitches and an amplitude defect of 30% of the rotor tip speed.

Figure 2*c*, from Camp & Day (1998), highlights the role of spike disturbances in triggering compressor stall even when a long-length-scale modal disturbance, with lower circumferential phase speed (20% of the rotor speed), is present. In this case, there is no apparent link between the short-length-scale disturbance (spike) and the long-length-scale disturbance (mode). The results of **Figure 2*c*** provide the first indication that both the modal- and spike-type disturbances are characteristic disturbances supported by the compressor. Which of these two disturbances will become unstable first and cause the compressor to stall is dictated by the compressor's design and operating conditions.

The schematic illustration in **Figure 3**, based on arguments offered by Emmons et al. (1955), can be used to explain how spike-stall inception can be initiated by blade-passage events. In a row of blades operating near the stability limit, a minor physical irregularity, or flow nonuniformity, can result in local flow separation and hence a reduction in the effective blade-passage flow area (i.e., an increase in flow blockage). This restricts the flow through the blade passage, thus diverting the incoming streamlines. On one side of the blockage, the streamline diversion causes increased incidence on the neighboring blade, whereas on the other side, it causes decreased incidence. The blade passage subjected to increased incidence becomes stalled, whereas the one already stalled unstalls. The stall cell thus propagates from blade to blade around the compressor. A stall cell such as this, in the early phases of formation, will only affect the flow around one or two blade passages.

2.2. Existence of Short-Length-Scale Disturbances Prior to Stall Onset

Using a cross-correlation analysis of signals from spatially adjacent sensors, Park (1994) analyzed measurements from the General Electric four-stage low-speed compressor showing that short-wavelength disturbances could be detected hundreds of rotor revolutions before the actual stall event occurred. These preliminary disturbances, discernable during the prestall phase (i.e., before the irretrievable onset of stall inception), repeatedly form and decay until a spike of sufficient amplitude emerges and the compressor finally stalls. The frequency of this forming-decaying activity increases as the flow rate is decreased toward stall. This type of behavior is most often seen when the compressor casing is oval-shaped or the tip clearance is asymmetric. Nevertheless,

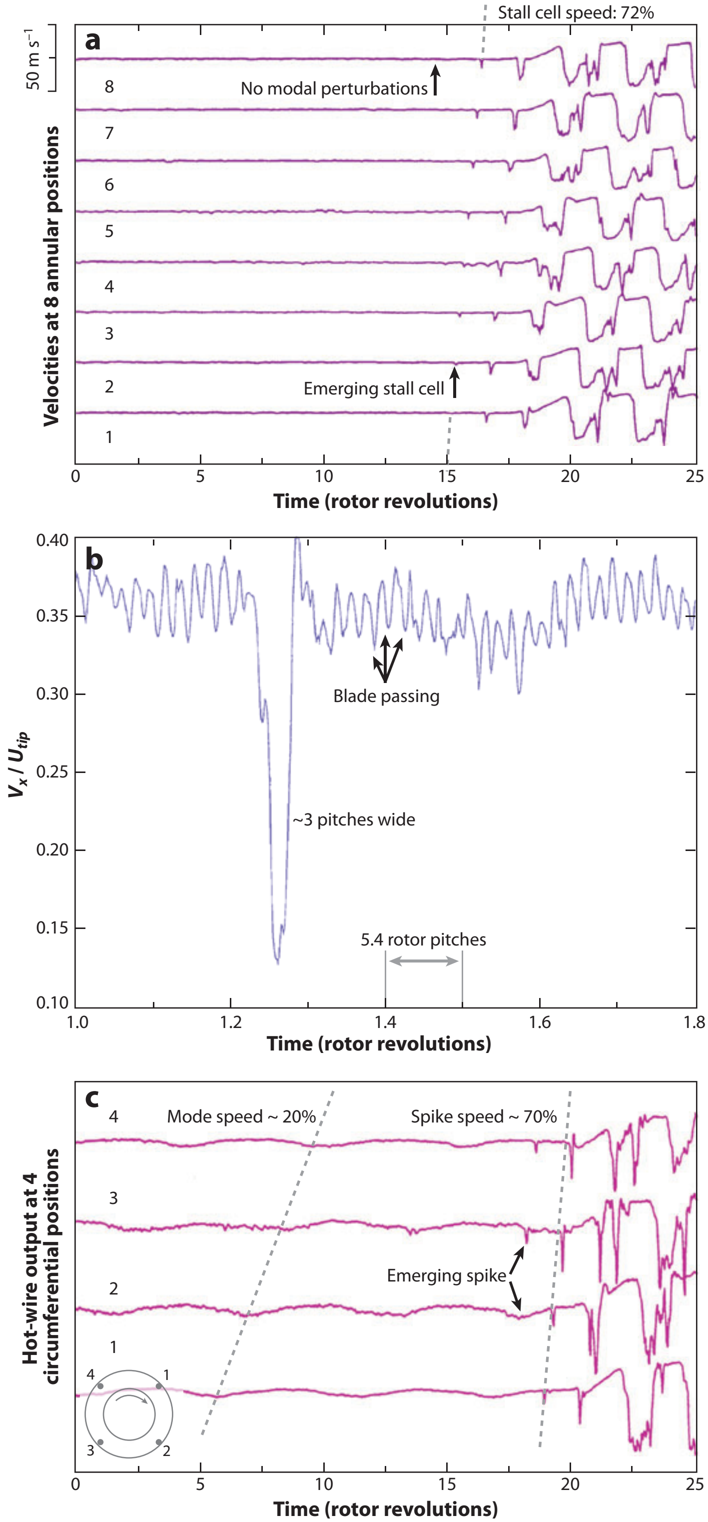


Figure 2

(*a*) Spike disturbance evolving into a mature stall cell in a low-speed compressor with no detectable modal disturbances prior to stall inception (Day 1993b). (*b*) Measured velocity trace, by Silkowski (1995) in the General Electric low-speed four-stage compressor rig, for a spike disturbance local to the rotor tip. V_x denotes the axial velocity component, whereas U_{tip} denotes the compressor's rotor tip speed. (*c*) Spike disturbance evolving into a mature stall cell in a low-speed compressor. Note that modal disturbances are present prior to spike formation but do not participate in the stalling event (Camp & Day 1998).

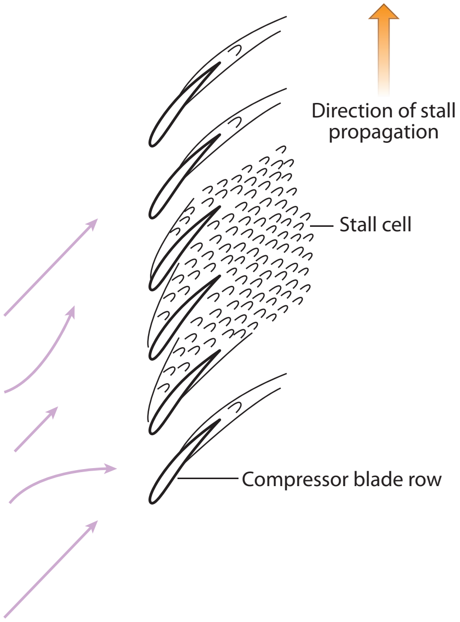


Figure 3
Day's (1993b) illustration of spike-stall development based on Emmons' exposition in 1955.

the implication is that the short-wavelength stall inception can be initiated by localized, nonlinear finite-amplitude disturbances; this contrasts with the progressive growth of long-wavelength modal disturbances, which behave in line with linear stability theory (Paduano et al. 2001).

Park also sought the best sensor location for detecting short-wavelength stall inception. He suggested that static pressure sensors at the first rotor exit appear to give the earliest and strongest signals. This observation may suggest that the initial spike-shaped disturbance assumes the largest amplitude at the rotor exit.

2.3. Stall Inception in High-Speed Multistage Axial Compressors

Data from high-speed multistage compressors (Day & Freeman 1994, Day et al. 1999, Escuret & Garnier 1996) show the variety and complexity of stall-inception patterns that may be encountered in these machines. In spite of the range of machines tested, a clear trend was observed; spike-type disturbances appear at low compressor speeds when the front end of the compressor is most highly loaded, and long-wavelength modal disturbances appear in the mid-speed range at which the loading is more evenly distributed throughout the machine. This change from spike to modal inception is in accord with the ideas and observations of Camp & Day (1998) in terms of changes in stage matching with rotational speed. The situation is more complicated at very high rotational speeds at which spikes sometimes appear at the rear of the machine (where the loading is highest), but in most cases the stalling pattern is too complicated to categorize. [In one of the compressors with relatively large inter-blade-row axial gaps, spike-type disturbances were observed throughout the speed range. It was hypothesized that the widely spaced blade rows may have favored localized spike-type disturbances rather than the modal type (see Section 5 below).] Thus, both spike-type disturbances and modal disturbances are seen with equal clarity in both low-speed (laboratory) and high-speed (aero-) compressors.

Compressor loading: measure of the pressure rise across a compressor blade row normalized by the inlet dynamic pressure relative to the blade row (i.e. the pressure rise coefficient)

The data of Hoss et al. (2000) appear to indicate that a compressor subjected to distorted inlet flow will exhibit spike-type stall inception throughout the speed range. Spakovszky et al. (1999) have noted that in a transonic compressor stage with radial inlet distortion, the inception process can switch from modal type (which would be the case for upstream uniform flow) to spike type when the distortion is present. Again, this observation supports the notion that both the modal- and spike-type disturbances are characteristic disturbances supported by the compressor.

Stall margin: a measure to the mass flow range between the design point and the lowest flow rate at which stable operation can be maintained

2.4. Experimental Observations on Compressor Response to Rotating Inlet Distortions

Longley et al. (1996) have examined the effect of a rotating inlet distortion on compressor stability, and the most important results are summarized in **Figure 4**. Out of the four compressors tested, two distinct patterns emerged representing the compressor's response to the rotating distortion (measured in terms of stalling flow rate versus the rotational speed of the distortion). One pattern shows a single resonance peak corresponding to a large decrement in stall margin when the inlet distortion is rotating at 40% of the rotor speed in the direction of rotor rotation (**Figure 4*a***); the other shows two resonance peaks at 25% and at 75% of the rotor speed (**Figure 4*b***). The compressors exhibiting one resonant peak were found to stall via modal inception, whereas the compressors exhibiting two resonant peaks stalled via spike-type inception. Viewing the rotating inlet distortion as an external stimulus (i.e., forcing), these results confirm the idea that modes and spikes are characteristic disturbances of the compression system, thus reinforcing the results of Section 2.1 and 2.3.

2.5. Summary of Experimentally Observed Features of Short-Wavelength Stall Inception

Short-wavelength stall inception is a prevalent type of fluid dynamic instability leading to stall and surge in low- and high-speed compressors. The experimentally observed features of short-wavelength inception are summarized here. In the initial phases, spike-type stall inception is characterized by a small, three-dimensional, localized disturbance confined to the rotor tip region where flow separation tends to start. The spike has a wavelength of the order of one to two blade pitches and a circumferential phase velocity of 70%–80% of the rotor speed during the inception stage. This circumferential phase velocity decreases to between 20% and 50% of the rotor speed as the spike grows (circumferentially, radially, and axially) into a mature stall cell. The time between the first detection of a spike and the final state of stall is generally less than five rotor revolutions. Short-wavelength stall inception appears to have stochastic origins, and a description based on linearized approximations may not be appropriate (see Section 5 below). Also, in contrast to modal stall, spike-stall inception often occurs at flow rates where the stagnation-to-static pressure rise characteristic has a negative slope (i.e., where the characteristic is still rising). (Modal-stall inception only occurs at the peak of the characteristic where the slope is zero.)

Broadly speaking, there are four phases of the evolution of a stall cell from inception to mature rotating stall: (*a*) prestall (see Section 3 below), (*b*) inception, (*c*) development, and (*d*) a final state involving the fully developed disturbance. In the majority of cases, spike inception appears spontaneously so that the prestall phase is generally uneventful. However, for compressors with tip-clearance asymmetry, the prestall phase is often characterized by the repeated formation and decay of short-wavelength disturbances, with the frequency of formation increasing as the compressor is throttled toward the stability limit. In the inception phase, the disturbances begin to grow; i.e., the start of the inception phase defines the pressure rise and flow rate at which stability

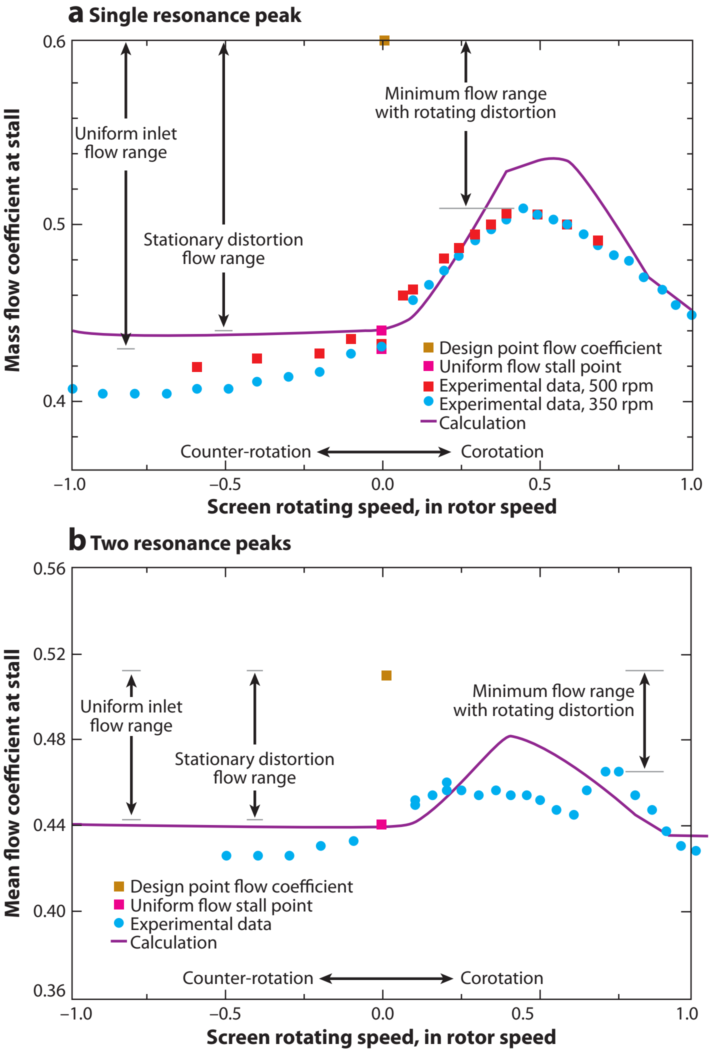


Figure 4

Two types of compressor resonance responses to rotating inlet distortion, reflecting the two types of stall-inception behavior, namely modes and spikes (Longley et al. 1996).

is irretrievably lost. Predicting the conditions under which instability will occur in a compressor requires an understanding of the flow processes leading to the onset of instability. The development phase includes all processes following inception and those prior to the final state and is of lesser importance here. The final state is, of course, rotating stall.

3. DETECTION OF PRESTALL ACTIVITY THAT MIGHT INDICATE THE IMMINENCE OF SPIKE-STALL INCEPTION

The localized nature of spike formation and the abruptness with which the flow breakdown occurs (Section 2.5) make the task of finding any kind of prestall warning signal technically challenging.

Nevertheless, numerous efforts have been made to devise techniques for sensing the imminent breakdown of the flow. Some techniques have proved more successful than others, but so far there does not seem to be one reliable method that can be used for all compressors. Below we present some of the work done in this field. In some cases, the objective has been to devise an online early warning system, whereas others use the analysis of recorded data to gain a better understanding of the flow breakdown process. Fast-response pressure transducers, or hot wires, are used throughout to extract information from the flow field.

From a philosophical standpoint, it is interesting to note that the stall warning techniques presented below all attempt to detect increasing unsteadiness in the run up to stall. For all this activity, however, no well-defined chain of events has been identified as a true precursor to the formation of a spike. (This is in contrast to the situation for long-length-scale stall inception in which growing modal activity can be traced from infinitesimal beginnings right through to stall-cell formation.) There is thus some justification for thinking that spike formation appears to have nonlinear, stochastic, origins.

Spatial Fourier analysis of signals from a circumferential array of transducers has often been used to provide amplitude and phase information. This method was proposed by J.P. Longley (personal communication) and was used by McDougall et al. (1990) to provide the first experimental evidence of prestall, long-length-scale, modal activity. As one might anticipate, the use of this technique for short-length-scale disturbances requires an unacceptably large number of high-response transducers. The difficulty here is to overcome the limits imposed by the spatial aliasing associated with weak signal strength spread among spatial harmonics [i.e., one can view the highly localized spike disturbance as having approximate delta-function characteristics (Lighthill 1975)]. Day et al. (1999) reported that although the spatial Fourier analysis technique proved useful for detecting modal activity in high-speed machines, it is not well-suited to detecting short-wavelength spike-like disturbances.

Cross-correlation of spatially adjacent signals, proposed and developed by Park (1994), can be a more effective technique for detecting prestall disturbances associated with the onset of spike-stall inception. Because the method uses the time history of a signal rather than the instantaneous signal, a large circumferential array of sensors is not required to resolve the spike disturbance at all times. Park used the method successfully to demonstrate the presence of spike disturbances that form and, almost immediately, decay during the prestall phase of inception (see Section 2.2).

A windowed space-time correlation was developed by Cameron & Morris (2007). The technique used unsteady surface pressures around the annulus upstream of the rotor leading edge to create a new scalar metric that is only sensitive to rotating disturbances between adjacent measuring points. The data indicated the presence of hundreds, or even thousands, of spike-type disturbances prior to stall. By offsetting the rotor within the circular casing, they observed that the spikes concentrated in the region where the tip clearance was the largest.

Traveling-wave-energy analysis, first implemented by Tryfonidis et al. (1995), can be used to detect any increase in traveling wave energy as a function of time just prior to the onset of stall. The wave energy is given by the difference between the positive-frequency and negative-frequency power spectra. The energy is computed for a fixed-time window that has the spectrum of the spatial Fourier modes within it and is advanced in time on a repetitive basis. The goal here is to detect the increase in wave energy well in advance of the onset of stall inception; this can serve as an early warning of the onset of instability if the traveling energy is within the frequency range of the instability modes. In contrast to the Fourier analysis technique mentioned above, traveling-wave-energy analysis has proved useful for providing early warning (50 to 100 rotor revolutions) of spike-type stall inception in a high-speed compressor (Day et al. 1999).

Dhingra et al. (2006) developed a correlation measure for detecting flow events prior to stall inception on a stochastic basis. The measure is obtained from autocorrelating the signal from high-response pressure transducers on the casing over the rotor tips. Appropriately normalized, the measure assumes a near-unity value when the pressure time trace is mostly periodic (i.e., when the compressor is operating well away from the surge line). However, as the boundary of stable operation is approached, this periodicity is progressively disrupted, resulting in the correlation measure decreasing steadily from unity. From available experimental data, Dhingra et al. (2006) infer that the correlation measure tends to dip from time to time. These dips increase in frequency and magnitude as the stability limit is approached. One might thus monitor the dips in the correlation measure below a predetermined threshold value to detect the imminence of stall. Although not directly alluding to the role of spike-stall inception, Christensen et al. (2008) and Tong et al. (2009) used the correlation measure to identify the prestall phase in (low- and high-speed) multistage compressors in their experiments on stall management.

There have been other works on developing stall detection and warning indices, such as those by Inoue et al. (1991), Hoss et al. (2000), and Tahara et al. (2004), but all use elements of the techniques discussed above.

In summary, the above efforts to detect prestall activity have, in some cases, been quite successful. The increase in prestall activity can usually be ascribed to a general increase in localized (blade-to-blade) unsteadiness, or to the momentary formation and decay of spikes—as is often observed when the tip clearance is eccentric. In no case, however, has anyone reported any kind of precursor that can be physically linked to the formation of a spike. We are thus still unable to determine, well in advance, when and where stall is likely to occur. This foreknowledge is essential for any effective stall-management system.

4. NUMERICAL SIMULATION OF SPIKE-STALL INCEPTION AND DEVELOPMENT

In this section we describe numerical computations, based on Reynolds-averaged Navier-Stokes equations, that serve to connect the blade-passage flow processes to spike-type stall inception.

Unsteady three-dimensional, single-blade passage, and multiblade passage, computations of spike-stall inception and development have been done using various CFD solvers. These computations can be divided broadly into two categories that complement each other: one with a focus on finding the simplest yet adequate computational means of defining the stability limit using single-passage calculations (Hoying et al. 1999, Vo 2001, Vo et al. 2008b) and the other with a focus on using larger computations to investigate the flow physics of spike inception through multiblade (Hoying et al. 1999, Vo 2001, Vo et al. 2008b) or full-annulus computations (Cameron et al. 2008, Chen et al. 2009, Hah et al. 2006). In addition, there have been recent publications on the use of numerical computations to explore prospective methods for controlling spike-stall inception (Chen et al. 2009, Vo et al. 2008a).

As described in Section 2, Day's (1993b) experimental measurements show that the spikes are not only localized circumferentially, but are confined to the tip region of the rotor blades. This suggests a possible link between the tip-clearance flow and spike-type cell formation. To investigate this link, simulations using single-blade- and multiblade-passage computations (for a compressor rotor) have been designed and implemented by Hoying et al. (1999), Vo (2001), and Vo et al. (2008b). The objective is to find the mechanisms and the conditions under which tip-clearance flow leads to the formation of short-length-scale disturbances. The single-blade-passage calculations are used to identify the flow features that set the limit of steady operation. This makes possible the idea that simple, single-blade passage, calculations can be used in the design phase of

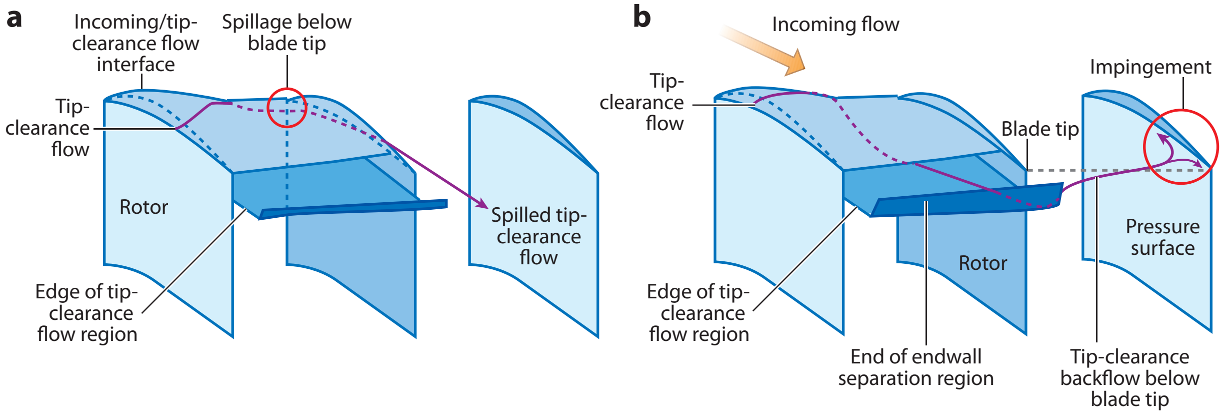


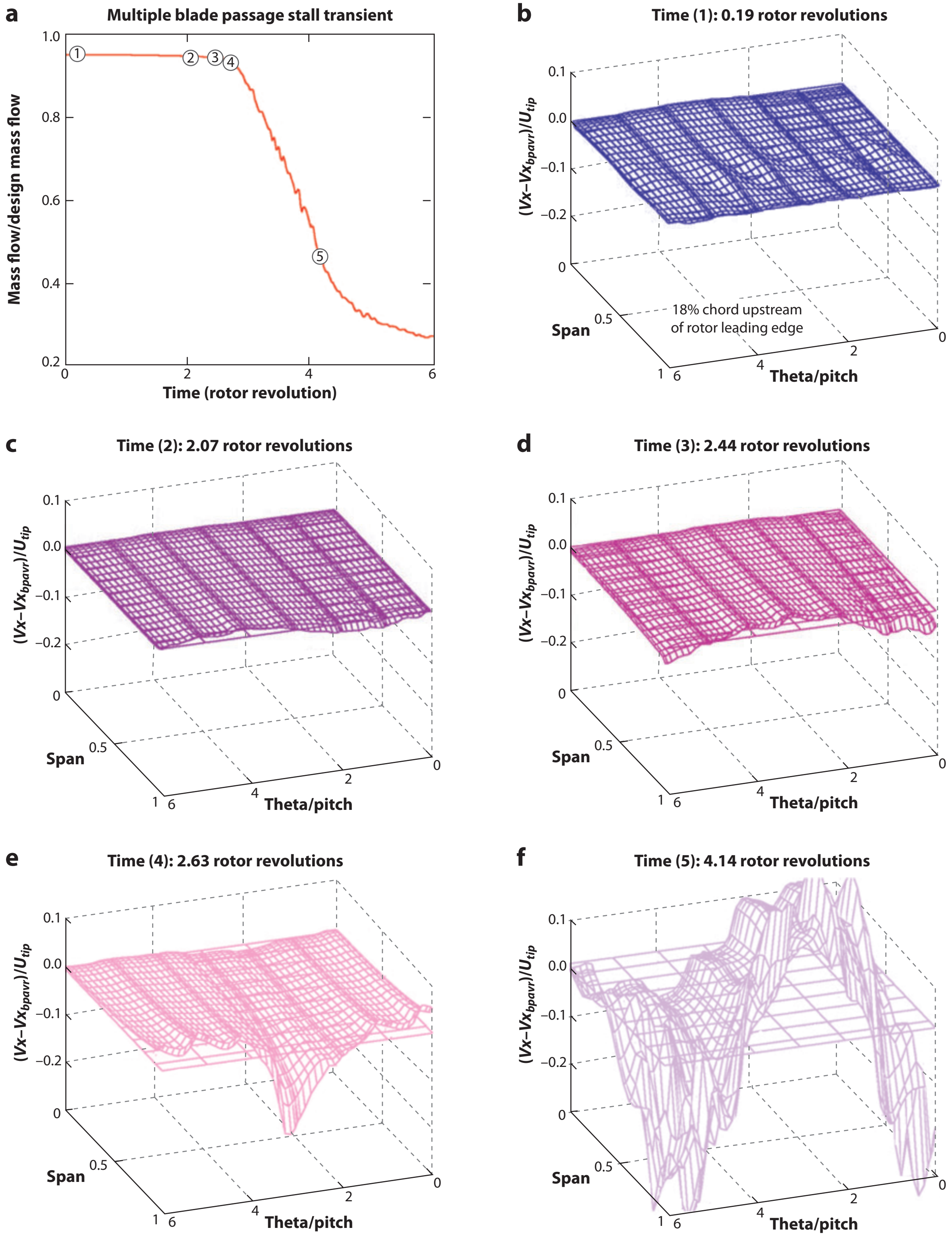
Figure 5

(*a*) Leading-edge tip-clearance flow spillage below the blade tip. (*b*) Reversal (backflow) of tip-clearance fluid below the blade tip (Vo 2001 and Vo et al. 2008b).

a compressor to check the width of the stall margin. The unsteady multiblade-passage solutions using six blade passages confirm the similarity of the flow features seen in the single-passage calculations with those seen in a multipassage environment.

Vo (2001) and Vo et al.'s (2008b) single-blade-passage computations show that when the solution limit is reached, the incoming/tip-clearance flow interface is aligned with the rotor leading-edge plane at the blade tip. By appropriately increasing the tip's exit pressure (beyond the steady solution limit) to achieve a rapid transient, the flow response suggests a spillage of tip-clearance flow to the adjacent blade passage ahead of the rotor leading edge and below (inboard of) the blade tip's radius. This idea of leading-edge spillage is illustrated in **Figure 5*a*** to show the path of tip-clearance fluid spilling into the next blade passage. The onset of flow spillage below the blade tip means that the incoming flow/tip-clearance flow interface lies parallel to the rotor leading-edge plane. This is cited as a common flow feature associated with compressors exhibiting spike stall. **Figure 5*b*** illustrates a second feature seen at a flow coefficient just below the flow solution limit. Fluid originating from the tip-clearance region of one blade moves across the blade passage into the neighboring passage by passing around the trailing edge. The trajectory of this fluid is such that there is impingement on the pressure surface of the adjacent passage. This reversal of the tip-clearance fluid from the first blade passage (essentially an end-wall separation with a circumferential relative velocity component) is referred to as tip-clearance backflow. Vo (2001) and Vo et al. (2008b) suggest that when these flow events (spillage of tip-leakage flow at the leading edge and tip-clearance backflow at the trailing edge) occur at the same time, a necessary requirement for spike formation is fulfilled.

Results from Vo's (2001) and Vo et al.'s (2008b) multiple-blade-passage stall simulation are shown in **Figures 6** and **7**. These results confirm that the flow features, and stability limit, derived from the single-passage solution are mirrored in the larger multipassage calculation. **Figure 6*a*** gives the time history of the mass flow during the stall transient. **Figures 6*b*–*f*** show the axial velocity V_X deviation from the passage-averaged value $V_{X_{bpavr}}$, normalized by the blade-tip velocity U_{tip}, at the different times marked in the mass-flow time history. The axial position of the plots is 18% chord upstream of the rotor leading edge, representative of hot-wire locations used in published measurements of spike disturbances. In **Figure 6*b*,*c***, no visible velocity defect at the blade tip is seen. In **Figure 6*d***, a short-length-scale disturbance is observed in the form of an axial


a
Multiple blade passage stall transient
Mass flow/design mass flow
Time (rotor revolution)
b
Time (1): 0.19 rotor revolutions
18% chord upstream
of rotor leading edge
c
Time (2): 2.07 rotor revolutions
d
Time (3): 2.44 rotor revolutions
e
Time (4): 2.63 rotor revolutions
f
Time (5): 4.14 rotor revolutions
$(Vx-Vx_{bpavr})/U_{tip}$
Span
Theta/pitch

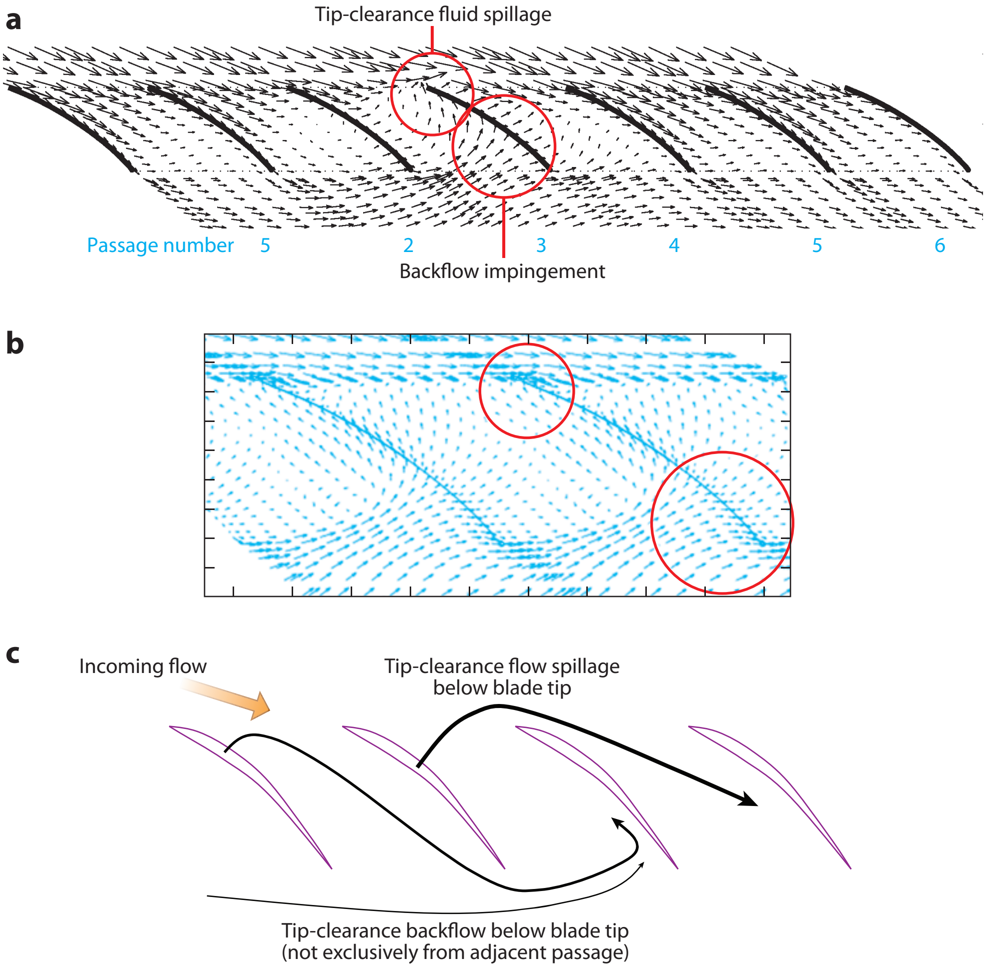


Figure 7

(*a*) Relative flow vectors at the blade tip at the time of stall transient shown in **Figure 6*e*** (Vo 2001 and Vo et al. 2008b). (*b*) Relative flow vectors at the blade tip in single-blade-passage computation at a flow coefficient near that of passage 3 in panel *a* (Vo 2001 and Vo et al. 2008b). (*c*) Simultaneous flow events in spike formation and the length scale of spike disturbance (Vo 2001).

velocity deviation near the casing. In **Figure 6*e***, a pronounced dip in velocity near the casing, which is localized over roughly two blade pitches, becomes visible and is accompanied by the start of a rapid drop in the mass flow. The disturbance grows quickly in amplitude and also becomes more two dimensional, i.e., more uniform across the span as seen in **Figure 6*f***. The computed phase speed, wavelength, and growth rate of the spike disturbance are roughly in agreement with experimental measurements.

Figure 6

Stall transient for multiple (six) blade-passage configuration; blade motion is from left to right, whereas the growing disturbance moves in the reverse direction relative to the blades. The three axes on the figure are axial velocity variation ($V_X - V_{X_{bpavr}}$) (nondimensionalized by rotor tip speed U_{tip}), span (from 0 at the hub to 1.0 at the tip), and blade passage number (from 0 to 6) (Vo 2001).

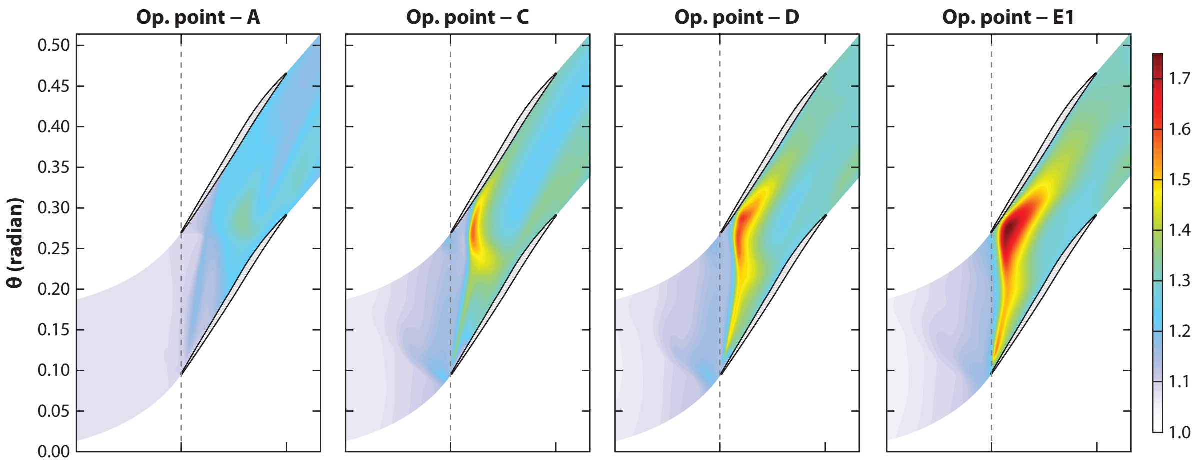


Figure 8

Color contour of casing entropy normalized by upstream value as the rotor is throttled from operating point A toward E1 at low flow, indicating the spillage of tip-leakage flow at the leading edge as the stall point is approached; tip-clearance flow corresponds approximately to the high-entropy region. Figure taken from Cameron et al. 2008.

The two threshold events, flow spillage at the leading edge and backflow at the trailing edge, proposed as necessary for spike-disturbance formation can be seen in both the multiple- and single-blade-passage solutions in **Figure 7**. The two sets of computations thus both show the same blade-passage flow processes as being responsible for the onset of spike-stall inception.

The multiple-blade-passage stall simulation also provides insight into the length scale of the spikes. The two threshold events for spike-disturbance formation involve a minimum of two or three passages in circumferential extent. In **Figure 7*a***, all the leading-edge spillage fluid from the passage 3 flows into passage 4 such that the disturbance is most pronounced for these two passages. The backflow tip-clearance fluid comes mainly from passage 2, but also perhaps from one or two passages earlier (**Figure 7*c***). In general terms, therefore, the spike disturbance has a length scale of three blade pitches, which is in accordance with experimental measurements (Day 1993b, Silkowski 1995).

The findings presented here have been backed up by recent large computational investigations on spike-stall inception. Examples of these works, consisting of unsteady three-dimensional, full-annulus simulations (involving one to two blade rows), include those by Hah et al. (2006), Bennington et al. (2007, 2008), Cameron et al. (2008), Lin et al. (2008), and Chen et al. (2009). Specifically, forward spillage of leakage flow (which can be viewed, on an approximate basis, to correspond to a region of high entropy in each blade passage in the tip region) at the leading edge becomes clearer in **Figure 8** as the stall point is approached. Likewise, results from the unsteady full (rotor) annulus simulations by Lin et al. (2008) show that the formation of a spike disturbance involves leading-edge tip-flow spillage as well as trailing-edge backflow that extended over approximately three blade passages.

5. ANALYTICAL MODELING OF SPIKE-STALL INCEPTION AND DEVELOPMENT

The experimental and the computational results presented thus far suggest that a sketch, such as that shown in **Figure 9** (Gong 1999), can be used to visualize the flow patterns around a

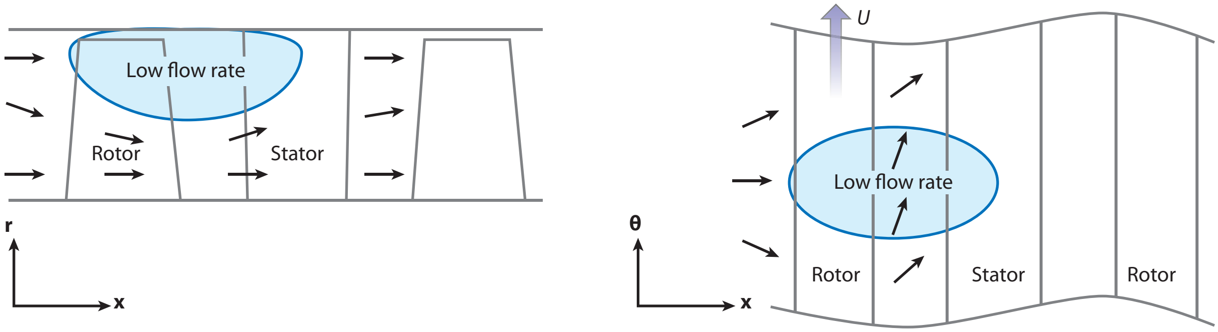


Figure 9

A sketch of the deduced flow pattern around a short-wavelength disturbance localized at the rotor tip; U denotes the rotor speed (Gong 1999).

short-wavelength disturbance. **Figure 9** illustrates the shape of a short-wavelength disturbance in the axial-radial (x,r) plane and in the axial-circumferential (x,θ) plane in the tip region of a blade row. The figure also shows the resulting flow field around the disturbed region. The flow patterns described here bring out two essential features needed in any flow model used to analyze spike-stall inception: (*a*) flow redistribution within the rotor-stator gap of the stage where the short-wavelength disturbance is located (thus a lumped compressor model cannot resolve this type of disturbance) and (*b*) flow redistribution within a blade row with the flow at the leading edge of a blade passage being significantly different from that in the rear part of the passage. This implies that a linearized model using the actuator-disk concept cannot be used to describe the flow field around a short-wavelength disturbance. This is in contrast to the case of a modal-type instability in which it has been shown that an actuator-disk description using linearized stability analysis is appropriate (Paduano et al. 2001).

Based on **Figure 9**, a flow model can be developed using the following conceptual framework. The action of a blade row that gives rise to pressure change, flow turning, and energy exchange can be replaced by a blade row with an equivalent body force. The key to suitable representation is the ability to characterize the body force in terms of the flow dynamics local to the blade row. The requirements are the following: (*a*) The physical laws (mass, momentum, and energy conservation) must be satisfied on a blade-averaged basis (i.e., the local flow features must be reflected on a blade-passage average basis); (*b*) there must be a correct dependence on geometry; (*c*) for prestall axisymmetric flow, the blade row must reproduce the overall pressure rise and turning angle; (*d*) the body forces must be able to respond locally to unsteady three-dimensional flow variations; and (*e*) the model must be able to capture the correct timescales and length scales of the developing instability (i.e., wavelength, phase speed, and growth rate).

Gong et al. (1999) have successfully used this type of modeling (linear as well as nonlinear) to simulate the unsteady three-dimensional flow in a multistage compressor. The model captures instability inception and the subsequent development of short-wavelength disturbances. The procedure requires the imposition of an initial disturbance of circumferential-radial extent comparable to a blade pitch, and local to the rotor tip region, for a duration of approximately 1/20 of a revolution. This constitutes an initial value problem in which the flow equations are time-stepped forward to track the (temporal and spatial) evolution of the imposed disturbance; if it grows in time, the system is unstable.

Actuator disk: region of infinitesimal extent in an internal flow situation (such as that involving a blade row or a compressor) across which sudden discontinuities in flow properties can be generated

Gong et al.'s (1999) computations captured the wavelength and phase speed of spike disturbances as well as their evolution to fully developed rotating stall. The calculated phase speeds and timescales were similar to those found experimentally. In addition, parametric studies using this model captured the critical angle of incidence for spike-stall inception seen by Camp & Day (1998), the stalling of the compressor (via spike disturbance) on the negatively sloped part of stagnation-to-static pressure-rise characteristic, and the observation that widely spaced blade rows favor localized spike-type disturbances rather than the modal disturbances. The complicated sequences of events described in Section 2 for spike-type stall inception can thus be adequately reflected in an integrated model (this does not imply that there exists a predictive capability for the onset of compressor instability).

6. CONDITIONS FOR STALL ONSET

From experimental observations, Camp & Day (1998) showed that in the compressor they used, spike-type stall inception occurred at a critical rotor-tip incidence. They used a four-stage, low-speed compressor with different IGV (inlet guide vanes) stagger angles to show that the stall points, for each stagger angle, line up on a constant rotor-tip incidence line whenever the compressor stalled via spike-type inception. As the measurements in **Figure 10** show, the stall-inception mechanism could be switched between spike-type and modal-type for the same rotor and stator settings by adjusting the IGV angles. The overall trend is that when the first rotor is highly loaded, the compressor tends to stall via spike-type inception (a short-wavelength disturbance in that particular blade row); otherwise the inception type is modal (a long-wavelength disturbance affecting the whole compressor).

Based on their observations, Camp & Day proposed a critical rotor-tip incidence that they used to explain the conditions under which spike or modal-stall inception might occur (**Figure 11**). When the critical incidence is reached before the peak of the compressor characteristics (**Figure 11*b***), the compressor will stall through short-wavelength disturbances; otherwise the compressor will stall at the peak pressure rise and will exhibit modal-stall inception (**Figure 11*a***). The connection between stall-inception type and rotor incidence is elucidated in

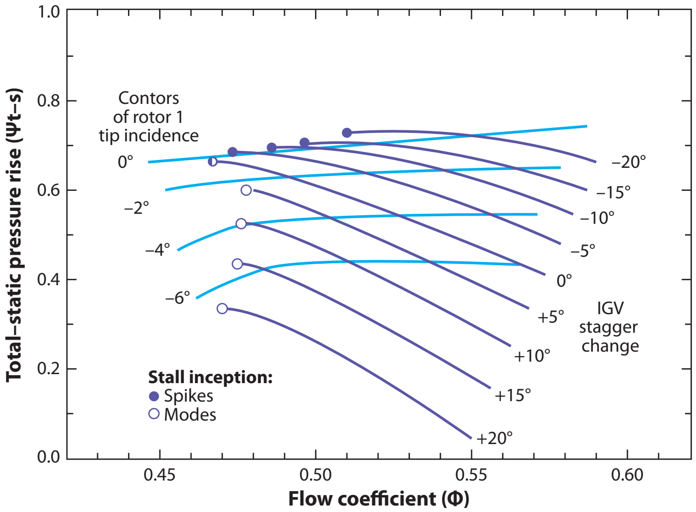


Figure 10

Effects of IGV (inlet guide vanes) stagger on stall-inception type, showing unique rotor-tip incidence for spike-stall inception. Figure taken from Camp & Day 1998.

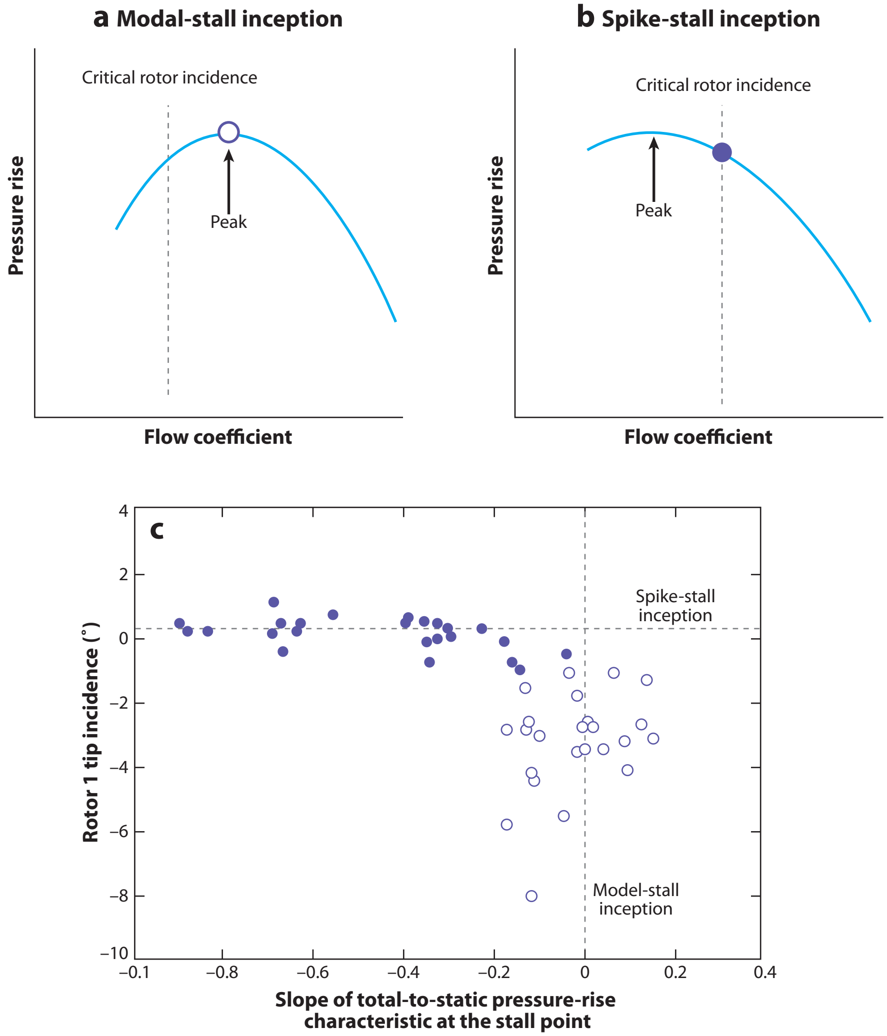


Figure 11

(*a–c*) Proposed criteria for determining the stall-inception type, (*a*) modal or (*b*) spike, of a compressor by Camp and Day (1998). (*c*) Their experimental results demonstrating the connection between stall-inception type and rotor incidence in a four-stage compressor.

the results of **Figure 11*c*** from a set of experiments in which the first-stage rotor-tip incidence was changed (by restaggering the IGVs or by rematching the compressor through changes in the stagger angle of the downstream stators). It is acknowledged, however, that the critical incidence angle is not unique and changes with rotor stagger or compressor design, and thus a better measure of criticality, based on some sort of tip-loading criterion, is required. One such criterion has recently been proposed by Simpson & Longley (2007). They used experimental results to define a meridional acceleration coefficient that appears to be able to separate modes and spikes.

Criteria for stall-inception type can also be inferred from Vo (2001) and Vo et al.'s (2008b) computational results. The two criteria that set the lowest flow coefficient at which a rotor blade passage can operate without the formation of spike disturbances are (*a*) the backflow of

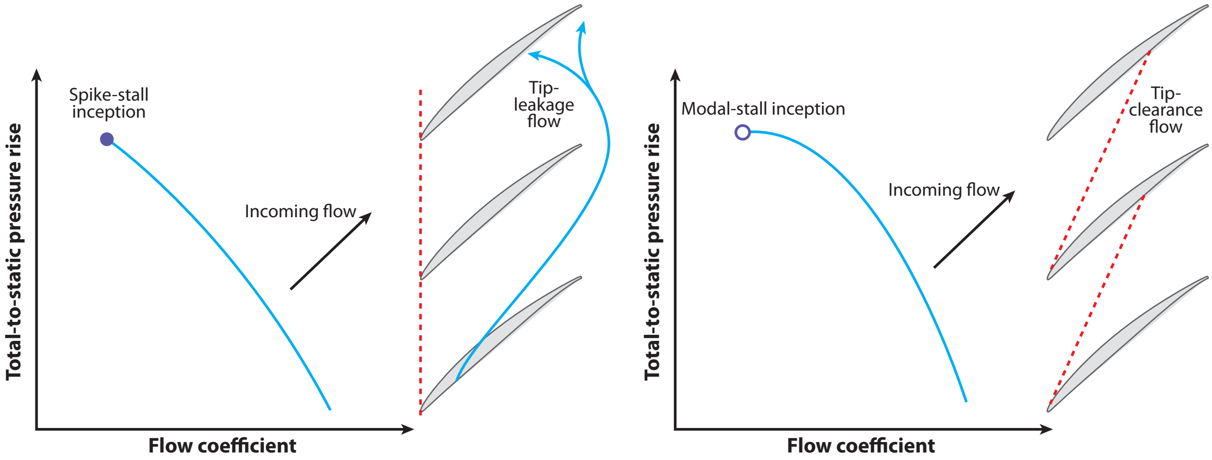


Figure 12

Proposed stall-inception criteria based on computations by Vo et al. (2008b); the red dashed line indicates the location of the incoming/tip-clearance flow interface.

tip-clearance fluid from adjacent blade passages at the trailing-edge plane below the blade tip and (*b*) the spillage of tip-clearance fluid ahead of the blade's leading edge below the blade tip into the next passage. As illustrated in **Figure 12**, when both criteria occur (simultaneously) before the peak of the compressor characteristics, the compressor will stall through short-wavelength disturbances; otherwise the compressor will stall at the peak pressure rise and will exhibit modal waves as its stall-inception type. Thus, the blade loading at which the backflow and spillage criteria occur simultaneously corresponds to the critical tip incidence that Camp & Day (1998) found for spike formation. This implies that we can substitute the criteria of spike-stall inception shown in **Figure 12** developed by Vo et al. (2008b) for the critical-incidence-angle criteria in **Figure 11** proposed by Camp & Day (1998).

7. EXPERIMENTAL SUPPORT FOR VO'S CRITERIA FOR SPIKE-STALL INCEPTION

Vo et al.'s (2008b) computational results show that a generic flow feature specific to rotors exhibiting spike-stall inception is the alignment (on the casing) of the interface (between the incoming flow and the tip-clearance flow) with the rotor leading edge near stall. This contrasts with modal-stall inception in which the interface lies inside the blade passage, as recently observed by Brouckaert et al. (2009). The earliest experimental observation to indicate the plausibility of this idea is the rotor-casing-oil pictures by Koch (1974) showing the movement of the interface toward the leading edge as the flow coefficient is reduced. The position of the interface results from a balance between the momentum of the incoming flow and that of the tip-clearance flow. As the flow coefficient is reduced, the axial momentum of the incoming flow reduces and the blade loading increases, thus increasing the momentum of the flow through the clearance gap. The consequence is a movement of the interface line toward the rotor leading-edge plane, as observed by Koch (1974) and Bennington et al. (2008).

The work by Saathoff & Stark (2000) also supports the circumferential alignment of the interface line with the rotor leading-edge plane. They examined a low-speed, single-stage compressor near the point of spike-stall inception and found that the stall limit occurred when the interface

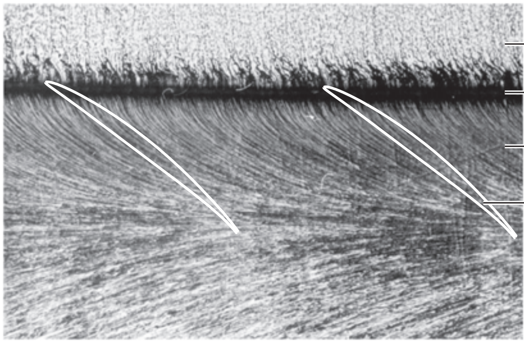


Figure 13

Rotor-casing-oil flow pattern near stall in a low-speed, single-stage compressor exhibiting spike-stall inception. Figure taken from Saathoff & Stark 2000.

was aligned with the leading edge, as indicated by the casing-oil flow pattern shown in **Figure 13**. We note that **Figure 13** shows a time-averaged picture, relying on wind shear and liquid viscosity, and is thus incapable of conveying anything specific about the instantaneous shape, or position, of the interface line.

Recent experimental measurements by Deppe et al. (2005) demonstrate the presence of both leading-edge spillage and trailing-edge backflow during spike formation in three different low-speed, single-stage compressors. **Figure 14** presents simultaneous pressure measurements upstream and downstream of the test rotor. (It should be observed, however, that the limited number of probes used around the circumference of the compressor in this experiment may not be sufficient to prove whether forward spillage and backflow occurred just before, or just after, stall.)

Recent experiments conducted by Bennington et al. (2007, 2008) have used a continuous running-flow visualization technique to examine the nature of the interface between the approach flow and the tip-leakage backflow in a transonic compressor. They used a low-viscosity liquid applied to the casing that was found to collect along a line that represented the time-averaged location of zero axial shear stress. This line moved forward as the compressor's mass flow decreased, and it was slightly upstream of the leading edge when the machine was stalled.

Although there is some experimental evidence to support the stall criteria proposed by Vo et al. (2008b), there is likewise some evidence to suggest caution at this stage. It is extremely difficult to obtain conclusive experimental evidence for forward spillage or backflow. The brevity of the flow breakdown process and the uncertainty of where, circumferentially, the event might occur are the principal difficulties standing in the way of indisputable evidence. Here lies the experimental challenge of the future.

8. PROSPECTS FOR CONTROLLING SPIKE-TYPE STALL INCEPTION

In contrast to modal-stall inception, the abruptness of spike-stall inception poses significant challenges for its detection (as noted in Section 3) and its control via active means. Active control consists of using real-time measurements from within the compressor to detect incipient stall events and then to apply appropriate action to suppress their growth and therefore delay stall onset. Since the discovery of spike-type stall inception, there have been numerous efforts to demonstrate the feasibility of extending the operating range of a compressor (for both low- and high-speed machines) by using active control (Christensen et al. 2008, Day 1993a, Freeman et al. 1998, Nie et al. 2002, Strazisar et al. 2004, Suder et al. 2001).

Day (1993a) demonstrated the control of spike-stall inception by determining when and where a spike begins to form and then applying actuation, in the form of small air jets, to suppress the spike and prevent it from developing into a mature stall cell. The effectiveness of the air jets, which are aimed at the flow in the rotor tip-gap region, can probably be attributed to the disruption of tip-clearance forward spillage (i.e., the removal of one of the necessary conditions for spike inception). More elaborate implementation of this technique involves the use of tip

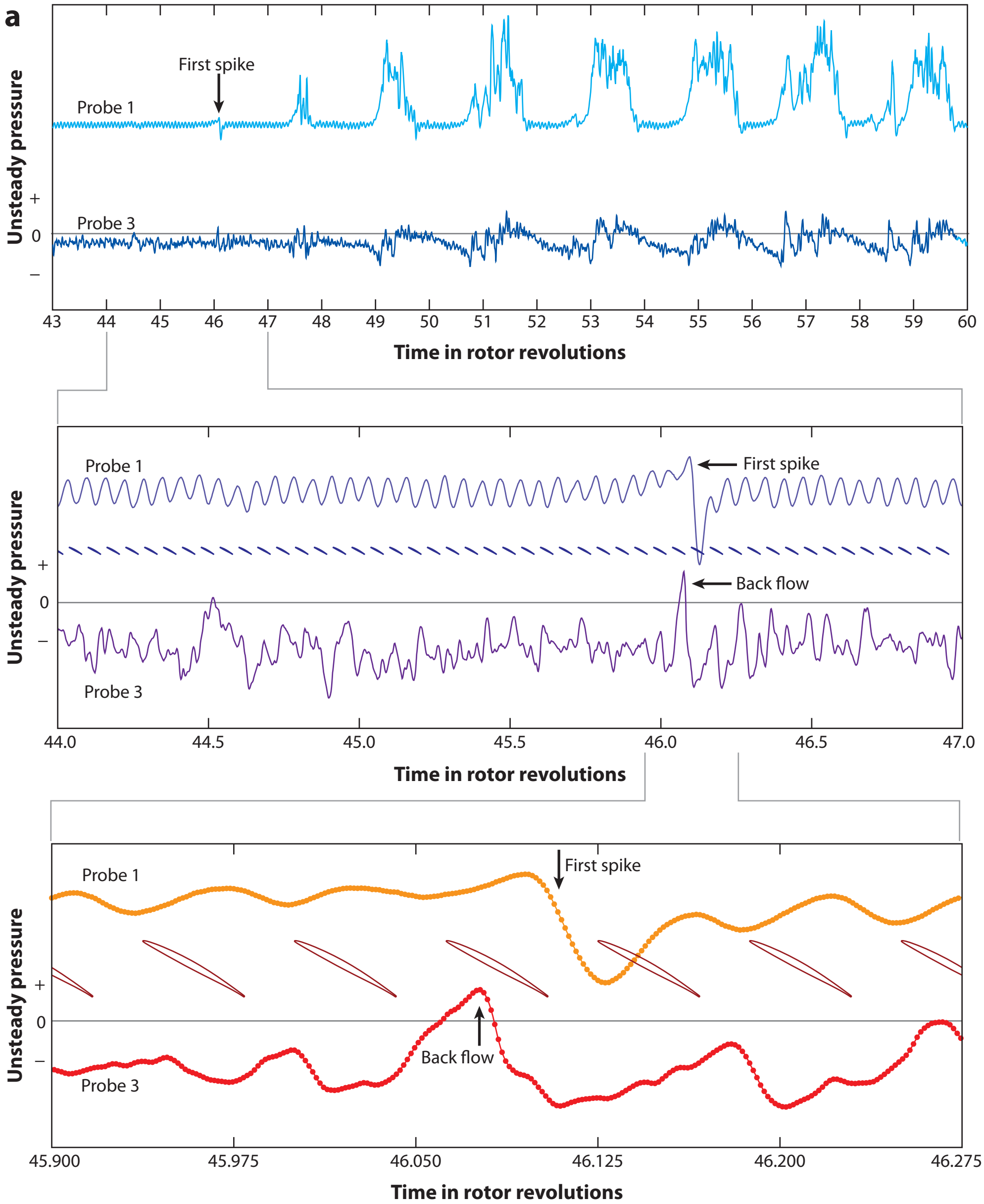


Figure 14

(*Continued*)

injection (Suder et al. 2001), end-wall recirculation (Strazisar et al. (2004), and micro–air injection (Nie et al. 2002). These active-control efforts often demonstrate 5% to 10% improvement in a compressor's operating range. However, stall suppression in this way may not be practical in multistage compressors where it is difficult to know which stage is likely to stall first. In this situation, a multiplicity of sensors and actuators (adding weight and cost) would be required to control stall throughout the speed range of the machine.

Recently, Wadia et al. (2006) (also Christensen et al. 2008) devised a stall management system for an advanced multistage high-speed compressor test rig. In this system, the output from high-response pressure transducers positioned over a preselected rotor is used, on-line, to monitor prestall activity and to provide remedial action (opening of a discharge valve) when the selected correlation parameter reached a certain cut-off level. In this particular case, the versatility of the system was limited by the placement of pressure sensors over one rotor only, but this could easily be remedied in future testing.

Another interesting approach to stall control is the use of casing treatment, both axially skewed slots and grooves cut into the compressor casing above the rotor path. Casing grooves generally give less stall-margin improvement than axially skewed slots, but the grooves have less of a

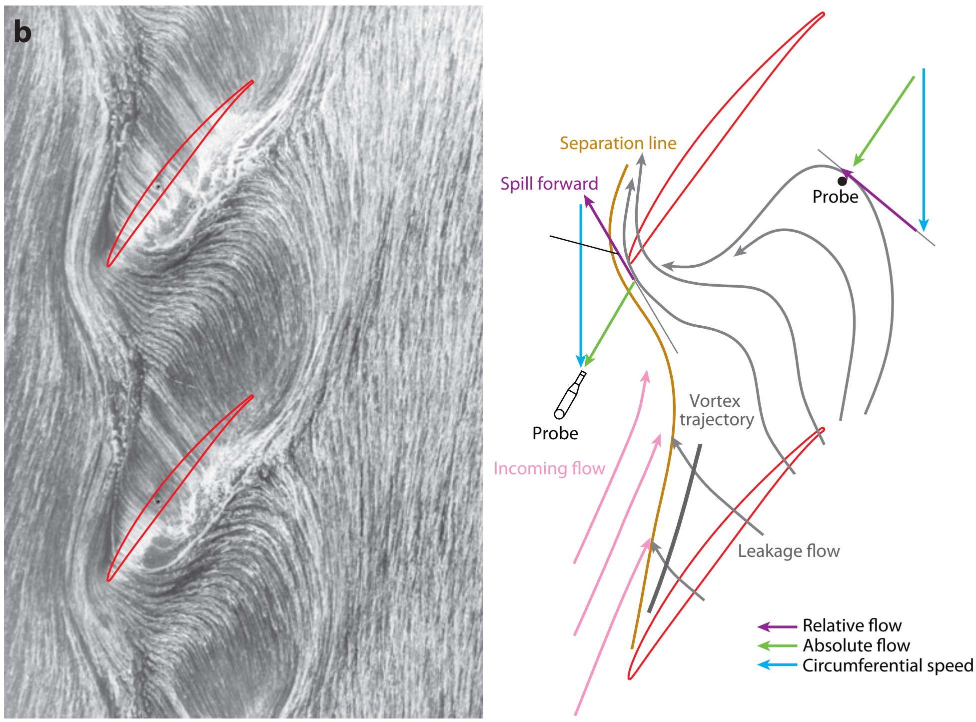


Figure 14

(*a*) Pressure measurements upstream and downstream of a single stage compressor rotor. Trace 1 of probe 1 in the top frame shows the evolution of an initial spike into a fully developed stall cell. The corresponding signal of probe 3 (trace 2 in top frame) shows axially backward directed flow (positive pressure signal) exactly at the position of the first spike in trace 1. The middle frame shows a close-up of the traces in the top frame, and the bottom frame shows a further close-up. These closer views show more clearly that the first spike in trace 1 is directly linked with the backflow indicated by probe 3. (*b*) End-wall flow features with topological details illustrated, showing that the spillage of the end-wall flow ahead of the blading (from rotor tip equivalent cascade experiments) is supported by low-energy fluid accumulated along the blade pressure surface.

detrimental effect on operating efficiency. Nolan's (2005) numerical computations show that casing grooves affect the trajectory of the rotor tip-leakage vortex and thus mitigate the radial transport of streamwise momentum away from the tip region resulting in stall-margin enhancement. However, in terms of our understanding of spike-stall inception, recent observations by Houghton & Day (2009) give rise to further complications when trying to link the tip-leakage vortex to the formation of spike-type disturbances. Houghton & Day show that a single casing groove, positioned approximately 50% of chord downstream of the rotor leading edge, can improve stall margin without interfering with the normal development of the tip-leakage vortex. If stall inception is linked to the tip-leakage vortex, then how can stall inception be delayed by a device that does not influence the vortex behavior? Here again is a challenge for future research.

As an interesting alternative to air jets, Vo et al. (2008a) proposed the use of glow discharge (plasma) actuation (Corke & Post 2005) over the rotor tips. The intention is to beneficially alter the tip-leakage flow dynamics (i.e., prevent clearance flow spillage) and thus to suppress spike-stall inception. The feasibility of such a strategy for stall control has been investigated on a computational basis (i.e., computational modeling of the stalling process and of the actuation system). There has not been any experimental demonstration of the effectiveness of the use of plasma actuators, but the idea has great potential due to its low power requirements and the unobtrusive mounting of the actuators in the compressor casing.

Finally it is worth noting that vortex core flows are susceptible to unsteady forcing (Bae 2001; Bae et al. 2004, 2005; Jacquin et al. 2003; Spalart 1998), and this could provide a physical basis for the control of a compressor's tip-leakage flows. The key idea is to excite the flow in the tip region using a spatially distributed actuation system at a frequency and mode shape necessary to create a resonance in the core of the leakage vortex. The hypothesis is that this will promote the dissipation of the tip vortices and therefore remove a part of the flow structure involved in spike formation. The potential advantages of the suggested control approach are the low use of power to drive the actuators and the high receptivity of the tip vortex core flow to this form of acoustic actuation. Such an approach for controlling the tip vortex flow has some analogies with the work of Reynolds et al. (2003) on the use of excitation to modify jet flows. Research effort on such an approach has not been implemented.

9. CONCLUDING REMARKS

There is a range of length scales that characterize the instability phenomena in an axial compressor. For example, the length scale of a spike-type instability is not much larger than the blade-to-blade spacing, whereas the final stall cell has a length scale equal to the compressor circumference. At the blade-passage level, there are flow features, such as blade-surface boundary layers and tip-clearance flows, that can play a role in stall inception. Given the richness of the flow processes, and the variety of length scales that define compressor performance, it is not difficult to appreciate the challenges involved in trying to predict the onset of compressor instability. Stall inception is complicated by tip-clearance flows, by compressor design, by downstream conditions, and by the chance concurrence of any number of mechanical events (e.g., shaft vibration coupled with the momentary coincidence of a mis-staggered blade and a local-casing imperfection). Moreover, there is also the problem of (random) incoming vortical disturbances. (The effect of such incoming flow perturbations is demonstrated by the example of a compressor that operates happily for minutes near the stability limit and then suddenly drops into stall for no apparent reason.)

Two themes are reflected in the review: One is how the discovery of a physical phenomenon (spike-stall inception) can spur on new efforts in a research field (aerodynamic instabilities) that had hitherto been almost stagnant; the other is the synergistic role of experiments and computations to provide an understanding of a phenomenon that is too complicated to be adequately resolved by measurement alone. The topic of stall inception, and particularly of spike-type stall inception (the most common type), has promoted new efforts to explain the flow breakdown process and has spun off the prospect of performance improvements by using the new technology of active stall and surge control.

With the growing thrust toward more environmentally friendly engines (with lower fuel usage), the concept of an intelligent engine emerges, one that utilizes remote sensing, on-line processing, and fast actuation to increase the performance of aeroengine compressors. The first step in creating the technology of stability control involves the development of appropriate models and measuring techniques to understand the physical phenomena that drive the instability process. The focus of this effort has been the study of the stall-inception process, as opposed to the more well-established study of fully developed stall. It is only by understanding the processes at work during stall inception that effective control architectures (sensors, actuators, control algorithms) can be designed to prevent, or delay, the occurrence of rotating stall.

Further efforts in this field of research are likely to embrace (*a*) improving CFD and modeling techniques to the point where the compressor stability limit can be reliably predicted and the flow in the tip region accurately described, (*b*) linking the fluid dynamic behavior in the rotor tip region more clearly with the actual process of stall inception, (*c*) using this knowledge to achieve better predictive/detective capabilities in the prestall phase of instability, (*d*) developing the sensors and actuators required for flow stabilization, and (*e*) developing effective control and engine-management schemes to reliably protect a multistage aeroengine compressor from rotating stall or surge.

SUMMARY POINTS

1. This review addresses the progress toward understanding compressor spike-stall inception since its discovery by Day in 1993.
2. It presents the experimental evidence for the existence of spike-type disturbances and the measurements designed to explain the physical and behavioral characteristics of this type of disturbance.
3. The implications of the characteristics of spike-type disturbances on their detection and suppression, as well as on the required attributes of the modeling approach to spike-stall inception, are discussed.
4. Existing data-analysis techniques used for the early detection of spike formation are reviewed, and efforts to identify pre-stall activity that might indicate the imminent formation of a spike-type disturbance are discussed.
5. The likely origin of a spike-type disturbance in the compressor and the relationship the disturbance has to the over-tip-leakage flows in the rotor blades are presented.
6. The computational studies undertaken to identify the hitherto unmeasurable fluid mechanic processes by which a spike disturbance comes into being are discussed.
7. Active and passive control techniques aimed at detecting and suppressing spike-type stall inception are reviewed.
8. The anomalies and unanswered questions surrounding the complex (and as yet not fully understood) phenomenon of spike-stall inception in axial compressors are discussed, along with their implications on future research.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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