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ACTIVE CONTROL OF ROTATING STALL IN AXIAL COMPRESSORS

Alexandru PETRESCU, Mircea BOªCOIANU, ªtefan-Mircea MUSTAÞÃ

Military Technical Academy - Bucharest
Corresponding author: ªtefan-Mircea MUSTAÞÃ, e-mail: stmustata@mta.ro

We start from the dynamic equations of the comprimating systems (Greitzer-1976) and we make a nondimensionalizing the mass flow rate, the pressure and the time to obtain the nondimensional governing equations. To analyse the stability we apply the Routh Hourwitz criterion and we determin the useful stability range for compressor stability. We propose an interesting concept of dynamic stabilization and we analyse the possibilities of improving the overall compressor performance.

Key words: active, control

1. INTRODUCTION

Surge has been studied to assess the effects of reversed flow on structural loading, and stall, to examine recovery problems and fatigue stressing of the blades. In recent times, however, the emphasis has shifted away from the study of the fully developed disturbance to concentrate on how these disturbances came into being, i.e., (the inception process).

Longley (1990) published a paper suggesting that active control could be applied to stall and surge to extend the useful operating range of compressor. The implementation of active control relies on the idea that if stall and surge can be shown to begin from small perturbations, it should be possible, by the introduction of artificially induced "friendly" perturbations, to create conditions in which the original perturbation can be held in cheek. This concept has therefore prompted a whole new series of experiments on stall and surge inception. Laboratory tests show that the instabilities do indeed begin as small perturbations and that the inception process is ordered and well defined. This work is now being followed up by detailed experiments on engine compressors to see if this is also true at high speed. The first of these experiments is presented here to give a back-to-back comparison of stall inception processes in low and high-speed compressors.

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2. STALL AND SURGE

In general term, *rotating stall* is a disturbance that affects the flow in the region of the compressor blading. The disturbance, once initiated, rotates about the compressor, causing severe blade vibration and, above all, a drop in overall pressure rise. In an engine, as opposed to a compressor rig, rotating stall, in all but its minor forms, will seriously restrict the flow into the combustion area leading to overheating and deceleration of the engine. Restarting of the stalled engine is then not possible until stall cell has been cleared and normal flow conditions restored. This usually requires an almost complete shutdown of the engine. In high-speed rigs, where the compressor is driven by an electric motor, blade vibration and temperature rise are the most serious consequences of rotating stall.

Surge, on the other hand, is an oscillation of the mass flow through the compressor and only occurs where a significant amount of pressure energy is stored downstream of the compressor. This is usually the case in an engine at high speed, where the combustion chambers act as an energy reservoir.

The equations governing the dynamics of this compression system are the particular cases of equations (1), (2) and (3) in Greitzer (1976).

$$\chi_c \frac{\mathrm{d}Q}{\mathrm{d}t} = f_1(Q_1) - (p - p_a) - \sigma_c\left(Q_1 - \overline{Q}_1\right) \qquad (1)$$

$$\frac{V}{\alpha^2}\frac{\mathrm{d}p}{\mathrm{d}t} = Q_1 - Q_2 \qquad (2)$$

$$\chi_t \frac{\mathrm{d}Q_2}{\mathrm{d}t} = (p - p_a) - f_2(Q_2) \qquad (3)$$

The term $\chi_t \frac{dQ_2}{dt}$ represents the inertia of the flow in the compressor; χ_c is proportional to the ratio of compressor length to diameter. χ_t is a similar parameter for throttle duct. $\sigma_c(Q_1 - \overline{Q}_1)$ is an experimentally determined term prescribed the flow resistance in the compressor duct; $\overline{\phi}_1 = \overline{Q}_1/(\rho A_c U)$ is non-dimensional mass flow rate, where U is the speed of compressor blade tip, ρ is the mean air density (a constant in the experiment A_c the cross-sectional area of the inlet duct.

In steady operation, the pressure drop $f_2(Q_2)$ across the throttle is a function of mass flow rate $\overline{Q}_2$. Under the conditions of the experiments, this function has found to be:

$$f_2(Q_2) = S\overline{Q}_2^2$$

where S is a coefficient depending on the throttle area A_t.

3. THE PROBLEM OF COMPRESSOR FLOW FIELD INSTABILITIES

We non-dimensionalize the mass flow rate using the quantity $\rho A_c U$, the pressure using $\frac{1}{2}\rho U^2$ and the time t using the characteristic time $1/\omega_H$, to obtain the non-dimensional governing equations (4), where:

$$\phi_1 = \frac{Q_1}{\rho{}^4_c U}\ ;\ \phi_2 = \frac{Q_2}{\rho{}^4_c U}\ ;\ P = \frac{p - p_a}{\frac{1}{2}\rho U^2}\ ;$$

$$Ø = \frac{f_1(Q_1)}{\frac{1}{2}\rho U^2}\ ;\ T = \frac{f_2(Q_2)}{\frac{1}{2}\rho U^2}\ ;\ \tau = \omega_{\mathrm{H}} t$$

$$B = \frac{\frac{1}{2}U}{\omega_H A_c \chi_c}\ ;\ \mu = \frac{\sigma_1}{\omega_{\mathrm{H}}\chi_c}\ ;\ \lambda = \frac{\chi_{\mathrm{c}}}{\chi_{\mathrm{t}}}$$

To find whether the system is stable or unstable, we follow established convention and examine its response to small perturbations when operating at a given condition. With given mean values $\overline{\phi}_1 = \overline{\phi}_2 = \overline{\phi}$, $\overline{P} = \Psi(\overline{\phi}_1) = T(\phi_2)$, we set $\phi_1 = \overline{\phi} + \delta\phi_1$, $\phi_2 = \overline{\phi} + \delta\phi_2$, $P = \overline{P} + \delta P$, $\Psi = \Psi(\overline{\phi}_1) + \Psi\delta\phi_1$ and $T = \overline{P} + T'\delta_2$ to arrive at the linear equations governing small-amplitude operation:

$$\left.\begin{aligned} \frac{\mathrm{d}\,\delta\phi_1}{\mathrm{d}\,\tau} &= B(\Psi'\delta\phi_1 - \delta) - \mu\delta\phi_1, \\ \frac{\mathrm{d}\,\delta\phi_2}{\mathrm{d}\,\tau} &= \lambda B(\delta P - T'\delta\phi_2). \end{aligned}\right\} \qquad (5)$$

These equations have solutions of the form $e^{s\tau}$, for which (5) corresponds to the characteristic equation:

$$s^3 + a_2 s^2 + a_1 s + a_0 = 0 \qquad (6)$$

where:

$$\begin{aligned} a_0 &= \lambda(BT' + \mu - B\Psi') \\ a_1 &= 1 + \lambda + B\lambda T'(\mu - B\Psi') \\ a_2 &= \lambda BT' + \mu - B\Psi' \end{aligned}$$

The Routh-Hurwitz stability criterion gives necessary and sufficient conditions for the real parts of all roots of (6) to be negative as:

$$a_0 > 0, \quad a_2 > 0, \quad a_1 a_2 > a_0 \qquad (7)$$

These constraints define the stable range of our compression system. By substituting the measured values and the functions into (7), the linear instability point at which the stability conditions (7) will just be broken and the compression system will surge can be predicted. We define the throttle characteristic corresponding to that instability point as the surge boundary.

The traditional approach to the problem of compressor flow field instabilities has been to incorporate various features in the aerodynamic design of the compressor to increase the stable operating range. Balanced stage loading and casing treatment are examples of design features that fall into this category. More recently, techniques have been developed that are based on moving the operating point close to the surge line when surge does not threaten, and then quickly increasing the margin when required, either in an open or closed-loop manner. The open-loop techniques are based on observation, supported by many years of experience, that compressor stability is strongly influenced by inlet distortions and by pressure transients caused by augmentor ignition and, in turn, that inlet distortion can be correlated with aircraft angle of attack and yaw angle. Thus, significant gains have been realized by coupling the aircraft flight control and engine fuel control so that engine operating point is continually adjusted to yield the minimum stall margin required at each instantaneous flight condition.

Closed-loop *stall avoidance* has also been investigated. In these studies, sensors in the compressor were used to determine the onset of rotating stall by measuring the level of unsteadiness. When stall onset was detected, the control system moved the operating point to higher mass flow, away from the stall line (Ludwig and Nemi, 1980). While showing some effectiveness at low operating speeds, this effort was constrained by limited warning time from the sensors and limited control authority available to move the compressor operating point.

4. A DYNAMIC STABILIZATION CONCEPT

We present the initial results of an alternative and fundamentally different means for attacking the problem posed by rotating stall. Here, we *increase the stable flow range* of an axial compressor by using closed-loop control to damp the unsteady perturbations that lead to rotating stall. In contrast to previous work, this dynamic stabilization concept improves the stable operating range of the compressor by moving the stall point to lower mass flows, discuss the design of the experimental apparatus, and present the experimental results.

The existing models for rotating stall inception in multirow axial compressors are typified by an equation for the velocity and pressure perturbations of the form:

$$\frac{\delta P_{compressor\ exit} - \delta P_{T\ compressor\ inlet}}{\rho U^2} = \left(\frac{d\psi}{d\phi}\right)\delta\phi - \lambda\frac{\partial\delta\phi}{\partial\theta} - \mu\frac{\partial\delta\phi}{\partial\tilde{t}} \quad (8)$$

Here, δP and δP_T are the static and total pressure perturbations, respectively, $\delta\phi$ is the nondimensional axial velocity perturbation at the compressor, λ and μ are nondimensional parameters reflecting the fluid inertia in rotor and rotor + stator + IGV, respectively, $\left(d\psi/d\phi\right)$ is the slope of the nondimensional compressor characteristic, and $\tilde{t}$ is a nondimensional time, $\tilde{t} = tU/r$.

Using these, Longley (1990) has shown that one can put Eq. (8) in a wave operator form. For the nth spatial Fourier coefficient, this is:

$$\left\{\left(\frac{2}{|n|}+\mu\right)\frac{\partial}{\partial\tilde{t}}+\lambda\frac{\partial}{\partial\theta}\right\}\partial\phi = \left(\frac{d\psi}{d\phi}\right)\partial\phi \quad (9)$$

The left-hand side of Eq. (9) is a convective operator corresponding to circumferential propagation with velocity $\left(\lambda/\left(2/|n|+\mu\right)\right)\cdot\left(\text{rotor speed}\right)$. The growth rate of the wave is dependent on the slope of the compressor characteristic. If $\left(d\psi/d\phi\right)$ is positive the waves grow; if negative they decay. Neutral stability (waves traveling with constant amplitude) occurs at $\left(d\psi/d\phi\right)=0$.

We can cast Eq. (9) in a form that is more useful for control by considering a purely propagating disturbance. The first Fourier mode will be of the form $e^{i\theta}$, so Eq (9) can be written as:

$$\left(2+\mu\right)\frac{\partial\delta\phi}{\partial\tilde{t}}+\left[i\lambda-\left(\frac{d\psi}{d\phi}\right)\right]\partial\phi = 0 \quad (10)$$

Thus far, the equations presented have been for flow associated with uncontrolled compressor dynamics. If, in addition, we model the control as due to perturbations in IGV stagger, $\delta\gamma$, we obtain the following equation for the first Fourier mode:

$$\begin{aligned}&\left(2+\mu\right)\frac{\partial\delta\phi}{\partial\tilde{t}}+\left[i\lambda-\left(\frac{d\psi}{d\phi}\right)\right]\partial\phi+\\&+\left[i\bar{\phi}\mu_{\mathrm{IGV}}-\left(\frac{d\psi}{d\phi}\right)-\left(\frac{d\psi}{d\gamma}-\bar{\phi}\mu_{\mathrm{IGV}}\lambda\right)\right]\delta\gamma- \quad (11)\\&-i\bar{\phi}\mu_{\mathrm{IGV}}\left(1+\mu-\frac{\mu_{\mathrm{IGV}}}{2}\right)\frac{\partial\delta\gamma}{\partial\tilde{t}}=0\end{aligned}$$

where $\bar{\phi}$ is the axisymmetric (annulus-averaged) flow coefficient, μ_{IGV} is the fluid inertia parameter for the IGV (inlet guide vanes), and $(\partial\psi/\partial\gamma)$ represents the incremental pressure rise obtainable from a change in IGV stagger, γ.

This is formally a first-order equation for $\delta\phi$; however, it must be remembered that the quantity of interest is the real part of $\delta\phi$. If we express $\delta\phi$ in terms of real and imaginary parts, $\delta\phi = \delta\phi_R + i\delta\phi_1$, then eq. (11), which is a coupled pair of first-order equations for $\delta\phi_R$ and $i\delta\phi_1$, becomes mathematically equivalent to a second-order equation for $\delta\phi_R$.

The form used in the system identification discussed below is thus second order. Another way to state this is that a first-order equation with a complex (or pure imaginary) pole is equivalent to a second-order system in the appropriate real-valued states.

5. CONCLUSIONS

The main purpose of this work is to determine the practical ways of improving the overall performance. It is physically possible to control rotating stall actively in an axial flow compressor and by doing so, obtain a useful extension of compresssor operating range

By using the active control we improve the recoverability needed, especially greater aircraft manevrability. Rotating stall could be supressed using active feedback control; it is possible for a low speed machine a 20% gain in compressor mass flow range. This work reinforce the view that the compressor stability is equivalent to the stability of low amplitude waves which travel about the machine circumferentially.

The results so far indicate that active control of large scale fluid mechanic instabilities such as rotating stall is very attractive.

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