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# CALCULATIONS OF EFFECTS OF ROTATING INLET DISTORTION ON FLOW INSTABILITIES IN COMPRESSION SYSTEMS

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## ABSTRACT

In the present paper calculations are presented to predict the post stall transient behavior and the onset of flow instabilities in axial compression systems with rotating inlet circumferential total pressure distortion. The effects of system parameters and the compressor characteristic are taken into account, and the effects on the boundaries of rotating stall and surge are investigated. It has been found that both the inlet distortion amplitude and rotating frequency have a strong effect on the stability and post stall transient behavior, and the rotating frequency has the same strong influence on the onset of surge as the influence on the onset of rotating stall. But the resonant response frequency (i.e., the rotating frequency of inlet distortion at which the greatest loss of stability occurs) strongly depends on the frequency at which the stall cell rotates. The study of the effects of system parameters shows that the loading and the flow coefficient of the compressor at the design point have a significant effect on the onset of instability, but they have little effect on the propagation speed of rotating stall and the resonant response frequency. The Greitzer B-parameter affects the onset of rotating stall, but it has little effect on the onset of surge. Some qualitative comparisons with available experimental results are made in this paper and show that the results are reliable.

## NOMENCLATURE

| | |
|---|---|
| Ac | compressor duct area |
| a | speed of sound |
| B | Greitzer B parameter (Eq. (11)) |
| DA | inlet total pressure distortion amplitude |
| $F_T$ | throttle characteristic function; $F_T^{-1}(\Phi)$ (Fig.2) |
| f | nondimensional propagation speed of rotating stall, referred to rotor speed |
| g | disturbance of axial velocity coefficient |
| H | semi-height of cubic axisymmetric characteristic (Fig.2) |
| h | circumferential velocity coefficient |
| $K_G$ | loss coefficient in IGV |
| $K_T$ | throttle coefficient |
| $K_{T0}$ | initial throttle coefficient (Fig.2) |
| $l_C$ | total aerodynamic length of compressor and ducts |
| m | compressor duct flow parameter |
| P | pressure |
| $P_T$ | total pressure ahead of entrance and following the throttle duct |
| R | mean wheel radius |
| $RK_T$ | relative throttle coefficient |
| $RK_{TF}$ | final relative throttle coefficient (Fig.2) |
| t | time |
| TCR | rate of throttle closing (Eq. (18)) |
| U | wheel speed at mean diameter |
| $V_P$ | volume of plenum |
| W | semi-width of cubic axisymmetric characteristic (Fig.2) |
| σ | disturbance potential |
| α | reciprocal time-lag parameter of blade passage |
| ε | inlet axial velocity nonuniform component |
| Ψ | total-to-static pressure rise coefficient |
| $\Psi_C$ | axisymmetric compressor characteristic |
| $\Psi_{CO}$ | shut-off value of axisymmetric characteristic (Fig.2) |
| Φ | axial flow coefficient in compressor |
| $\Phi_T$ | flow coefficient of throttle duct, referred to entrance duct area |
| φ | local axial flow coefficient |
| ρ | density |
| θ | angular coordinate around wheel |
| ξ | time, referred to time for wheel to rotate one radian |
| η | axial distance measured in wheel radius |
| Δ | fluctuation value |
| ω | rotating frequency of inlet distortion, referred to rotor speed |

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**Subscripts**

o at the entrance of the compressor or initial value

E at the exit of the compressor

I at the exit of the inlet nonuniform generator

S at end of exit duct or in the plenum

**Superscripts**

* total parameter

\- annulus averaged parameter

## INTRODUCTION

Because of the adverse effects of inlet flow distortion on gas turbine engine operation, the inlet distortion problem has received considerable attention, and a substantial experimental and theoretical work has been done on this topic. One of the most important aspects of the problem is the assessment of the effect on flow stability in compressors that a given inlet distortion produces. Many methods have been presented for computing this loss in stability. For further investigation of the problem, it becomes very important to predict the post stall transient behavior and the influence of system parameters. Moore (1985) has theoretically analyzed the stall transient behavior of a compression system with steady inlet distortion by extending Moore-Greitzer's model (Moore and Greitzer, 1985). Later Ishii and Kashiwabara (1989) expanded Moore's method by using spectral method to take into account the influence of higher harmonics. In a previous paper (Hu et al., 1993), a method was presented to predict the post stall transient behavior of compression systems and the effects of system parameters for both cases with uniform and nonuniform inlet flow. The method can also be used to deal with the problem of rotating inlet distortion.

Rotating inlet distortion is very important for two-spool or three-spool aero-engines and could arise from a low pressure compressor in rotating stall generating a nonuniform total pressure profile at the downstream high pressure compressor. This problem has been experimentally investigated by Ludwig et al. (1973) in a single rotor compressor. Their experimental results showed that the boundary of rotating stall of a compressor strongly depends on the frequency at which the inlet distortion rotates. Hynes et al. (1987) theoretically analyzed the influence of rotating frequency of inlet distortion on the stability boundary of a compressor. They got similar results as those obtained experimentally by Ludwig et al. But the model developed by Hynes et al. can only provide an eigenvalue analysis so that it can not be used to predict the influence of inlet distortion on the post stall transient behavior of compression systems and the interaction between rotating stall and surge. Recently Longley et al. (1994) did the experimental work in several multistage low-speed compressors. They found that multi-stage compressors can have more than a single resonant response frequency. But all their results did not deal with specific details, such as, whether the rotating distortion has the same influence on the boundary of surge as the influence on the boundary of rotating stall, and what the resonant response frequency depends on, although the experimental results (Ludwig et al., 1973, Longley et al., 1994) showed that it is close to the natural propagation speed of rotating stall or the modal wave propagation speed which occurs for compressor B. In this paper we will systematically analyze the effects of rotating inlet distortion on the onset of instabilities and the development of rotating stall, and the effects of system parameters as well. Some results are very similar to those observed in the past experiments.

## BRIEF DESCRIPTION OF THE MODEL

The model was described in detail in the previous paper (Hu et al., 1993) so that only a brief description will be presented here. The basic compression system to be analyzed is shown in Fig.1. It consists of a nonuniform inlet flow generator, an inlet duct, an axial compressor of N stages of an annulus area Ac, an exit duct, a plenum of volume Vp, a throttle, and a throttle duct. We shall

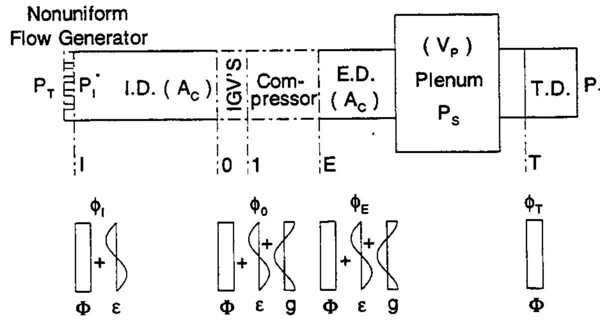


FIG.1 SKETCH OF THE COMPRESSION SYSTEM AND NOTATIONS

assume that the system can be satisfactorily modeled by Moore-Greitzer's theory of finite amplitude disturbance in a multistage axial compressor (Moore and Greitzer, 1985). The theory has been further developed to predict the influence of inlet distortion by Moore (1985). Some approximations used by Moore (1985) have been adopted too. These approximations may briefly be summarized as follows: (1) The compressor is of sufficiently high hub-to-tip ratio so that a two-dimensional treatment is valid. (2) It is a low speed compressor and Mach numbers are small. In the compressor and its ducts the flow will be considered incompressible. Therefore, the annulus averaged axial velocity coefficient $\Phi$ will be constant through out the inlet duct and compressor, though it may vary with time. In the inlet duct an inviscid flow is assumed too. (3) In the inlet duct and compressor, the local (in $\theta$) axial velocity coefficient at any location is divided into an annulus averaged component $\Phi$, an inlet distortion component $\varepsilon$, and a disturbance axial velocity component. The disturbance axial component is excited by the compressor and is assumed to be irrotational, though the mean velocity is rotational because of the inlet velocity nonuniformity. (4) The plenum dimensions are large compared to those of the compressor and its ducts, so that the velocity and fluid accelerations in the plenum can be considered negligible. The pressure in the plenum is spatially uniform, though possibly varying in time. (5) In this paper, the simplifying approximation (Moore and Greitzer, 1985)

$$\frac{dh}{d\theta} = -g \qquad (1)$$

will not be used, where h and g are the circumferential velocity coefficient and disturbance axial velocity coefficient at the entrance of the compressor. Moore and Greitzer (1985) took only the first term of the Fourier series solution of the disturbance potential σ

$$\sigma(\eta,\theta,\xi) \approx e^{\eta}(a_1\sin\theta + b_1\cos\theta); \quad \eta \le 0 \tag{2}$$

and inferred equation (1). This simplifying relation seems to be quite accurate in general, but the condition i.e. equation (2) will limit its application, and using this simplifying approximation, a set of third order partial derivative equations is obtained so that the numerical solution gets very difficult. We assume that any order Fourier component of the disturbance potential decays exponentially in the axial direction (η), but is independent on its spatial harmonic number

$$\sigma(\eta,\theta,\xi) \approx [\sum_{n=1}^{\infty} \frac{1}{n}(a_n\sin n\theta + b_n\cos n\theta)]e^{\eta}; \quad \eta \le 0 \tag{3}$$

It is clear that equation (3) includes equation (2), and using this simplifying approximation, a set of governing equations is obtained which are first order both in angle and in time.

The governing equation to describe the local annulus dynamic pressure rise is

$$\psi'(\theta,\xi) = \psi_C(\Phi+\varepsilon+g) - l_C\frac{d\Phi}{d\xi} - (m+\frac{1}{\alpha})\frac{\partial g}{\partial \xi} - \frac{1}{2\alpha}\frac{\partial g}{\partial \theta}$$
$$-\frac{1}{2}(1-K_G)[\frac{\partial g}{\partial \theta}]^2 - l_C\frac{\partial\varepsilon}{\partial\xi} - [\frac{\partial g}{\partial\theta} + \frac{1}{2\alpha}]\frac{\partial\varepsilon}{\partial\theta} \tag{4}$$

where

$$\psi'(\theta,\xi) = \frac{P_S - P_I^*}{\rho U^2} \tag{5}$$

is the actual local pressure rise coefficient of the system. g will be used to describe rotating stall, should it occur. If g is not zero and varies cyclically with time, rotating stall occurs. So g is a function of ξ and θ. $\Psi_C$ is the axisymmetric compressor characteristic and modeled as a cubic function in this analysis

$$\psi_C(\Phi) = \psi_{CO} + H[1 + \frac{3}{2}(\frac{\Phi}{W}-1) - \frac{1}{2}(\frac{\Phi}{W}-1)^3] \tag{6}$$

The second, third and fourth terms on the right side of equation (4) present the influence of the unsteadiness of the flow through the system and the circumferential nonuniform flow because of the occurrence of rotating stall on the local pressure rise of the system. The fifth term is influenced by the IGV. $K_G$ is the loss coefficient of IGV. The last two terms take the influence of inlet distortion into account.

According to the definition of the disturbance potential, we have

$$g = (\frac{\partial\sigma}{\partial\eta})_{\eta=0} \tag{7}$$

and know that the cyclic integration of the third and fourth term on the right side of equation (4) must vanish. So integrating equation (4) in circumferential direction, the annulus averaged axial momentum equation can be written as

$$\bar{\Psi}'(\xi) + l_C\frac{d\Phi}{d\xi} = \frac{1}{2\pi}\int_0^{2\pi}[\psi_C(\Phi+\varepsilon+g) - \frac{1}{2}(1-K_G)(\frac{\partial g}{\partial\theta})^2]d\theta$$
$$+\frac{1}{2\pi}\int_0^{2\pi}[-l_C\frac{\partial\varepsilon}{\partial\xi} - (\frac{\partial g}{\partial\theta} + \frac{1}{2\alpha})\frac{\partial\varepsilon}{\partial\theta}]d\theta \tag{8}$$

Applying the continuity equation to the system, one will find that the equation of balance of entering, leaving, and stored mass of the plenum is the same as that derived by Moore and Greitzer (1985)

$$\frac{d\psi}{d\xi} = \frac{1}{4l_C B^2}[\Phi(\xi) - F_T^{-1}(\psi)] \tag{9}$$

where

$$\psi = \frac{P_S - P_T}{\rho U^2} = \psi' - \frac{\Delta P^*}{\rho U^2} \tag{10}$$

and

$$B = \frac{U}{2a}\sqrt{\frac{V_P}{L_C A_C}} \tag{11}$$

$F_T$ is the throttle characteristic and modeled as

$$F_T = \psi = \frac{1}{2}K_T\Phi_T^2 \tag{12}$$

The throttle line and the axisymmetric characteristic are shown in Fig.2. $\Delta P^* = P_T - P_I^*$ is the difference in total pressure when a flow passes through the nonuniform flow generator, and is determined by the generator. It may vary with circumferential angle and time.

The above equations are the governing equations of the theoretical model, which only include first order derivatives without linearization. Under the influence of an initial disturbance, they can be used to determine the solutions of axial flow coefficient Φ, total-to-static pressure rise Ψ, and the growth/decay of rotating stall cells for both cases with uniform and nonuniform inlet flow. For the numerical approach of the equations, an explicit first order time marching method is used.

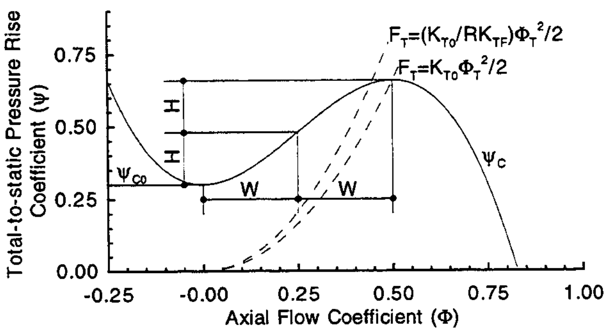


FIG.2 AXISYMMETRIC COMPRESSOR CHARACTERISTIC AND THROTTLE LINE

## NUMERICAL RESULTS

The nonuniform velocity component ε and nonuniform total pressure component $\Delta P^*$ may be functions of angle and time, and are determined by the inlet nonuniformity generator. In the present paper, in order to investigate the influence of rotating inlet total pressure distortion, $\Delta P^*$ is given as the following:

$$\frac{P_T - P_I^*}{\rho U^2} = (DA)[1 - \sin(\theta - \omega\xi)] \quad (13)$$

where

$$DA = \frac{\Delta \bar{P}^*}{\rho U^2} = \frac{P_T - \bar{P}_I^*}{\rho U^2} \quad (14)$$

is the inlet total pressure distortion amplitude, and ω is the rotating speed referred to rotor speed, at which the inlet distortion rotates. The distribution of $\Delta P_I^*/\rho U^2$ is shown in Fig.3.

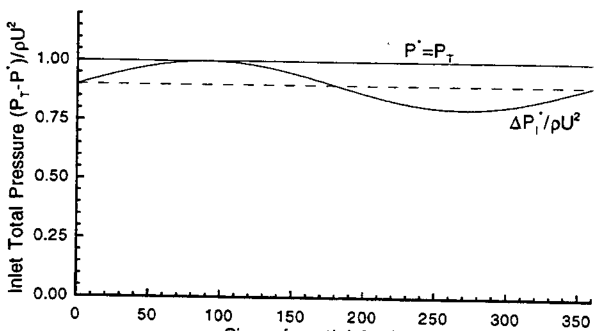


FIG.3 INLET TOTAL PRESSURE PROFILE

## Initial Conditions

Unless specified , the initial steady operating point of the compression system is taken at the peak of the axisymmetric compressor characteristic, which is the natural instability inception point of the compression system for the case with no inlet distortion. At this point, we have:

$$\Phi_0 = 2W, \quad \Psi_0 = \Psi_{CO} + 2H$$

and $K_{TS}$ is defined as the throttle coefficient of the throttle line passing through this point.

If the throttle characteristic, equation (12), is rewritten as

$$F_T = \frac{1}{2}\frac{K_{T0}}{RK_T}\Phi_T^2 \quad (15)$$

where

$$RK_T = \frac{K_{T0}}{K_T} \quad (16)$$

$K_{T0}$ is the initial throttle setting coefficient, which is determined by the initial steady operating point. $RK_T$ is called the relative throttle coefficient here and its initial value is 1.0.

In order to induce flow instabilities in the system, an initial disturbance must be presented. The initial disturbances include both angular nonuniformity, which is necessary for rotating stall like motion to be induced, and a time-dependent disturbance like closing a throttle. The initial circumferential disturbance is simply taken as

$$g_0(\theta) = A_0 \sin\theta; \quad A_0 = 0.005 \quad (17)$$

## Throttle Closure

According to equation (15), when the initial operating point is known, the throttle closure process can be described by the variation of the relative throttle coefficient $RK_T$ with time. In this paper, $RK_T$ is taken as a linear function of ξ

$$RK_T = 1.0 - TCR*\xi; \quad \xi \le \xi_F \quad (18)$$

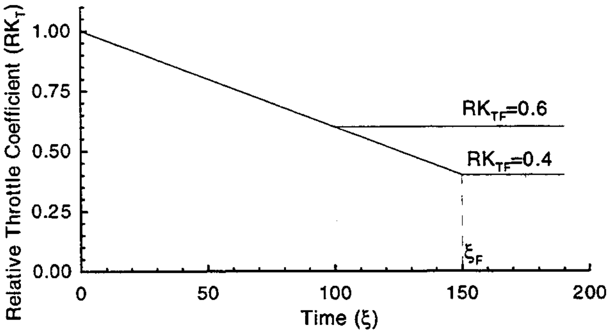


FIG.4 THROTTLE CLOSURE PROCESS

where TCR is a given rate at which the relative throttle coefficient decreases. Its closure process is shown in Fig.4. The closure starts at an initial operating point, $RK_T$=1.0, and ends at a closed throttle setting $RK_{TF}$<1.0, after which the throttle setting stays constant. When the post stall transient behavior of compression systems is analyzed, $K_{T0}$ is taken to be $K_{TS}$ and $RK_{TF}$ is changed. However, if the influence of an inlet distortion on the stability of compression systems is to be predicted, $RK_{TF}$=0.99 is taken and $K_{T0}$ is changed to determine the inception point of instability.

As a basis for comparisons to come, a base case is specified as a set of typical values of system parameters:

$\alpha$=1/3.5 m=1.75 $l_C$=8.0 H=0.14 W=0.25

$\Psi_{CO}$=0.30 $RK_{TF}$=0.99 B=0.40 DA=0.10 TCR=0.005

The values of axisymmetric compressor characteristic parameters, $\alpha$ and m all are similar to those used by Moore and Greitzer (1985). The total pressure distortion amplitude level (DA=0.1) is close to that used by Longley et al. (1994) In their experiments, the screen produced a roughly square-wave total pressure distortion with an amplitude corresponding to 1.2 dynamic heads based on a mean inlet velocity.

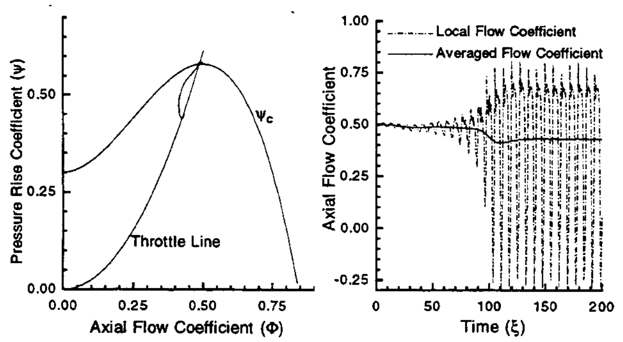


FIG.5 THE POST STALL TRANSIENTS WITH UNIFORM INLET FLOW (DA=0.0)

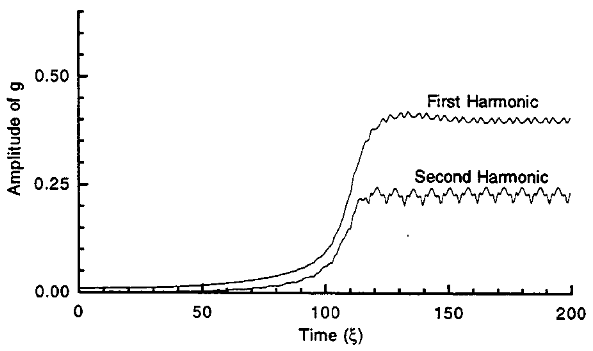


FIG.6 THE TIME HISTORY OF THE AMPLITUDES OF THE DISTURBANCE AXIAL VELOCITY COEFFICIENT FOR THE SAME CASE AS FIG.5

## Effects on the Post Stall Transients

The basic features of post stall transient behavior with uniform inlet flow have been discussed in the previous papers (Hu et al., 1992a, 1992b). Fig.5 shows the transient behavior of rotating stall for the case with $RK_{TF}$=0.95, $\Phi_0$=0.5, and DA=0.0. The time history of the amplitudes of the first and second Fourier components of its disturbance axial velocity coefficient g is shown in Fig.6. It is a typical rotating stall motion, and it can be seen that before the rotating stall is fully developed, there is a prestall period ($\xi$=90) during which the amplitude of travelling waves is much smaller than that of fully developed rotating stall waves. Fig.7 shows that under the influence of steady inlet distortion with DA=0.1, the initial disturbance leads to a pure rotating stall quickly. The amplitude of the disturbance axial velocity coefficient in the compressor oscillates at a constant frequency, which is very near the value of the rotating frequency of the stall cell, after the rotating stall is fully developed. In this case, the inlet distortion is steady. In other words, when fully developed, the stall cell rotates at a constant frequency f (f=0.86). So the relative frequency at which the stall cell rotates referred to the inlet distortion is f because $\omega$=0 for steady inlet distortion, and the amplitude oscillates at the frequency f too.

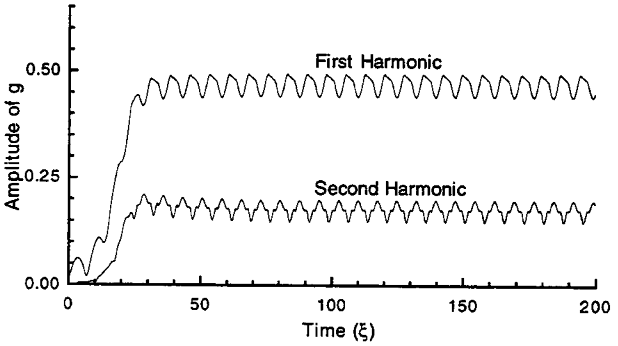


FIG.7 THE TIME HISTORY OF THE AMPLITUDES FOR THE SAME CASE AS FIG.6, EXCEPT THAT DA=0.1

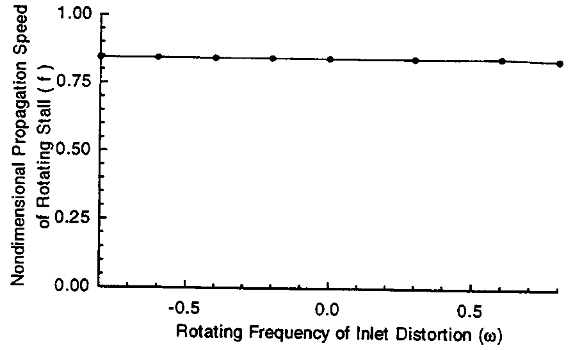


FIG.8 THE EFFECT OF ROTATING SPEED OF INLET DISTORTION ON THE PROPAGATION SPEED OF ROTATING STALL

The feature that steady inlet distortion has little effect on the propagation speed of rotating stall has been verified by experimental data and theoretical results. For rotating inlet distortion, the result in Fig.8 shows that the rotating speed of inlet distortion has no effect on the propagation speed of rotating stall either.

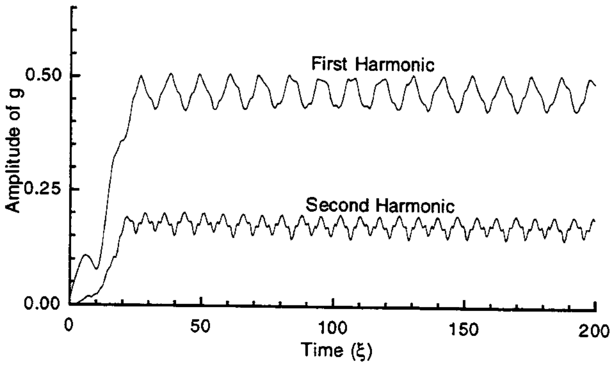


FIG.9 THE TIME HISTORY OF THE AMPLITUDES FOR THE SAME CASE AS FIG.7, EXCEPT THAT ω=0.30

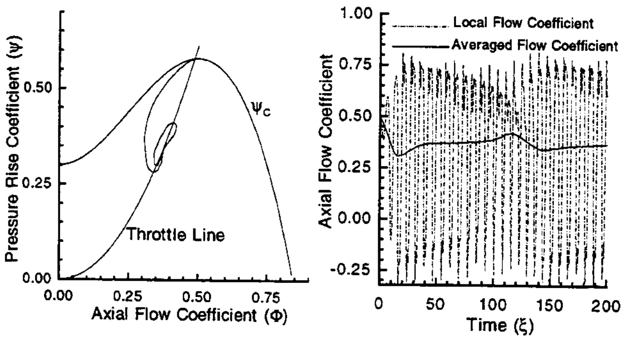


FIG.10 THE POST STALL TRANSIENTS FOR THE SAME CASE AS FIG.5, EXCEPT DA=0.1 AND ω=0.80

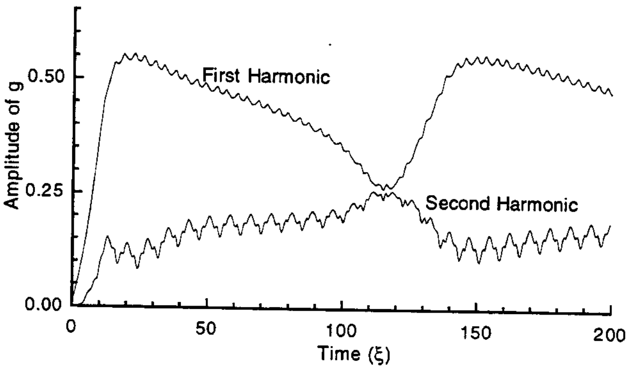


FIG.11 THE TIME HISTORY OF THE AMPLITUDES FOR THE SAME CASE AS FIG.10

Fig.9 shows that when the inlet distortion rotates at a frequency ω, the amplitude of fully developed rotating stall waves oscillates at the relative frequency (f-ω). But when ω is near the value of f, the annulus averaged flow coefficient oscillates at a low frequency. The operating point of the compression system undergoes a limit cycle type of motion like surge, during which the amplitude of the rotating stall waves oscillates, as shown in Fig.10 and Fig.11. The above results show that the inlet distortion and its rotation speed have a strong effect on the transient behavior of rotating stall, and under the influence of inlet distortion, rotating stall cell waves are not steady again even if the rotating stall is fully developed. When the rotation speed of inlet distortion is close to the propagation speed of rotating stall, such an influence becomes very strong.

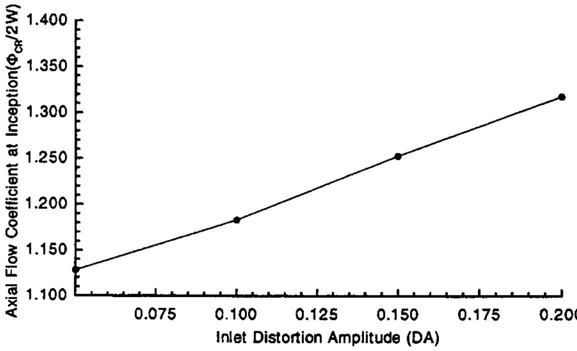


FIG.12 THE EFFECT OF INLET DISTORTION AMPLITUDE ON STALL INCEPTION FLOW COEFFICIENT FOR THE BASE CASE

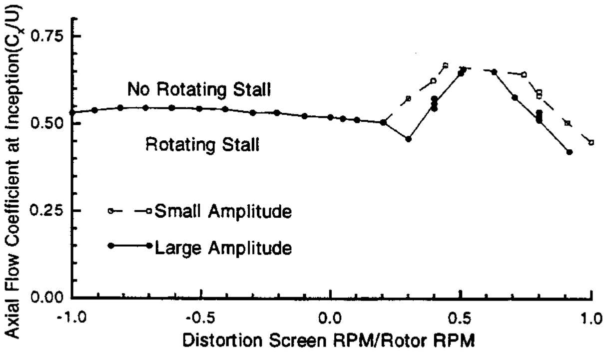


FIG.13 THE EFFECT OF DISTORTION ROTATION RATE ON COMPRESSOR STALL ONSET (Ludwig et al., 1973)

## Analysis of the Resonant Response Frequency and Influence of Time Lag and B parameter on Stability

It is important to know the instability inception point of a compression system. It is well known that inlet distortion will degrade the stability margin of a compression system, and both inlet distortion amplitude (DA) and propagation speed of rotating inlet distortion (ω) have a great effect on the instability inception point. In order to examine these issues, detailed calculations have been carried out here. Fig.12 shows the effect of the inlet total pressure distortion amplitude on the value of flow coefficient at the instability inception point. It is similar to the past experimental data and experience that the value of inception flow coefficient increases with the increase in distortion amplitude. The experimental result obtained by Ludwig et al. displayed in Fig.13 shows that the rotating frequency of inlet distortion has a strong effect on the inception flow coefficient of rotating stall and the resonant response frequency is near 50% of the rotor speed. The calculation result in Fig.14 is very consistant with the experimental result in Fig.13. Only in this computing case the natural propagation speed of the rotating stall is about 86% of the rotor speed. So the stability margin of the system degrades strongly when the rotating speed of the inlet distortion becomes close to this value. It is larger than that in Fig.13.

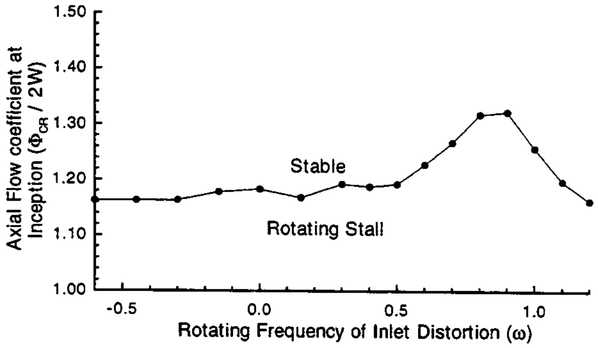


FIG.14 THE EFFECT OF ROTATING SPEED OF INLET DISTORTION ON FLOW COEFFICIENT AT INCEPTION OF ROTATING STALL FOR THE BASE CASE

The reciprocal time-lag parameter $\alpha$ has a significant influence on the propagation speed of rotating stall. Fig.15 shows that the propagation speed of rotating stall decreases with the increase in $\alpha$. In order to verify the conclusion that the resonant response frequency is close to the natural stall cell propagation speed, the influence of the rotating frequency $\omega$ on the inception flow coefficients of the system is quantified for the cases with f=0.86, 0.63, 0.52 and o.35 respectively and shown in Fig.16. These results demonstrate that the resonant response frequency is close to the natural stall cell propagation speed, and all results show that the counter rotation of inlet distortion ($\omega$<0) has a less adverse effect on the stability margin of compression systems than the steady inlet distortion. These results are quite consistent with the test data obtained by Ludwig et al. (1973) in a single rotor compressor and those with a single peak in a stall margin

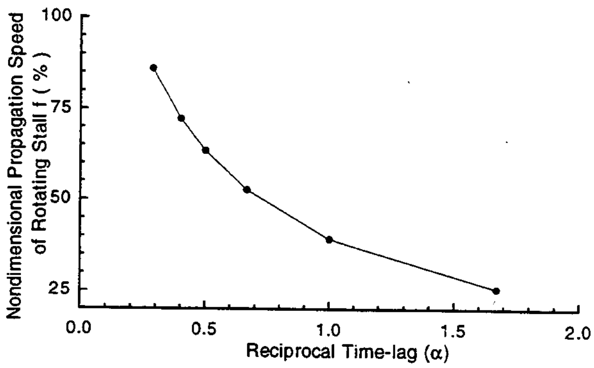


FIG.15 THE EFFECT OF $\alpha$ ON THE NONDIMENSIONAL PROPAGATION SPEED OF ROTATING STALL

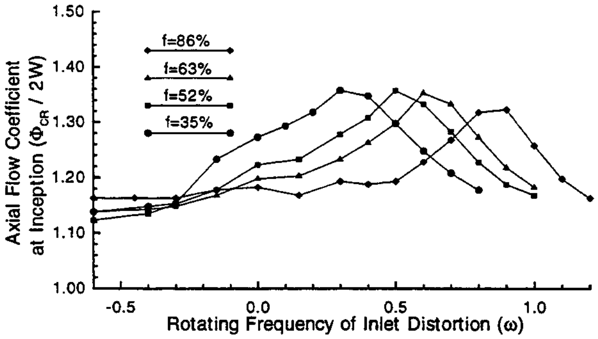


FIG.16 THE EFFECT OF f ON THE RESONANT RESPONSE FREQUENCY

degradation for compressor A and compressor B obtained by Longley et al. (1994). Although the peak stall margin degradation for the compressor B occurs when the distortion rotates at the modal wave speed, the difference between the stall cell speed and the modal wave speed is quite small, and the degradation has only a little change in the region of the peak. For our model, in all above cases, the modal wave has the same propagation speed as the stall cell.

There are two kinds of flow instabilities in compression systems, rotating stall and surge. As we know, rotating stall is a nonaxisymmetric two-dimensional form of instability. We can understand easily that inlet circumferential distortion and propagation speed of rotating inlet distortion have a strong effect on the inception point and transient behavior of rotating stall. The above results have verified this. Surge has traditionally been regarded as a one-dimensional disturbance with axisymmetric flow fluctuations. In recent times, however, it has become increasingly clear that rotating stall plays an important part in initiating a surge event, and during a cycle of surge rotating stall can be observed. The experimental data obtained by Tryfonidis et al. (1994) showed that rotating perturbations exist prior to surge. And it has been verified by many experimental data and theoretical results that steady inlet distortion has a strong influence on the boundary of surge, but until now we do not know if the propagation speed of rotating inlet distortion has a strong influence on the boundary of surge.

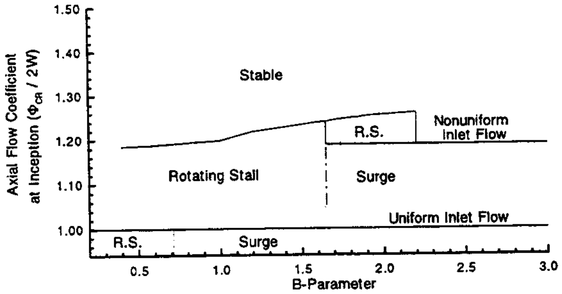


FIG.17 THE EFFECT OF PARAMETER B ON STALL FLOW COEFFICIENT AND INSTABILITY MODE

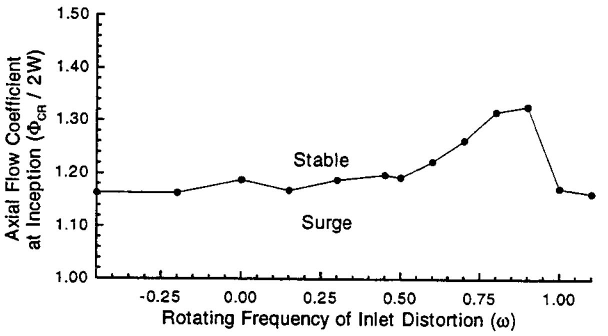


FIG.18 THE EFFECT OF ROTATING SPEED OF INLET DISTORTION ON FLOW COEFFICIENT AT INCEPTION POINT OF SURGE FOR B=2.6

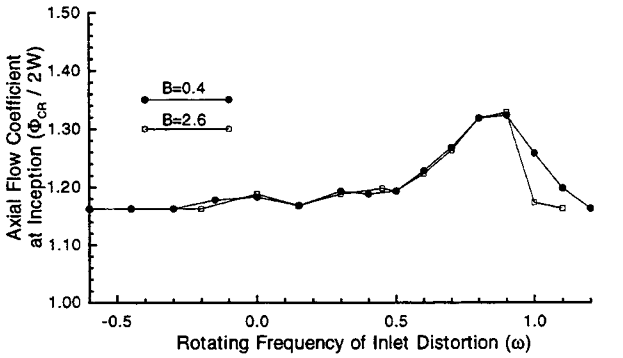


FIG.19 COMPARISON BETWEEN BOUNDARIES OF ROTATING STALL AND SURGE

It is well known that the Greitzer B-parameter has a strong effect on the response mode of instability. Fig.17 shows the result of the influence of the parameter B on the response mode of instability and the inception flow coefficient of instabilities for both cases with uniform inlet flow and with the inlet distortion. For the case with uniform inlet flow, there seems to be a clear transition from rotating stall to surge. This occurs at a value of B=0.71. And the value of B does not have an influence on the inception flow coefficient as evident in Fig.17. For the case with inlet distortion, however, when B<1.65 the response mode of instability is rotating stall, and when B>2.2 the response mode is surge, but when 1.65<B<2.2 there are two boundaries. The inception flow coefficient of rotating stall increases with the increase in B parameter, but it does not affect the boundary of surge. Fig.17 shows that the response mode of instability is surge for the system with B=2.6. For the case of B=2.6 the influence of the propagation speed of the inlet distortion on the boundary of surge is shown in Fig.18. From this figure one can clearly see that the rotating frequency has a strong effect on the boundary of surge and the resonant response frequency is close to the natural propagation speed of rotating stall of the system too. The influence of ω on the boundary of surge is quite similar to that on the boundary of rotating stall, shown in Fig.19. As we know, parameter B has no effect on the propagation speed of rotating stall, and prior to surge, classic surge or deep surge, rotating perturbations can be observed. The result in Fig.20 shows that rotating perturbation exists prior to the surge and rotating stall is present over a part of the cycle of surge. Clearly, rotating stall plays an important role in initiating surge and the rotating speed of inlet distortion has a strong effect on the boundary of surge.

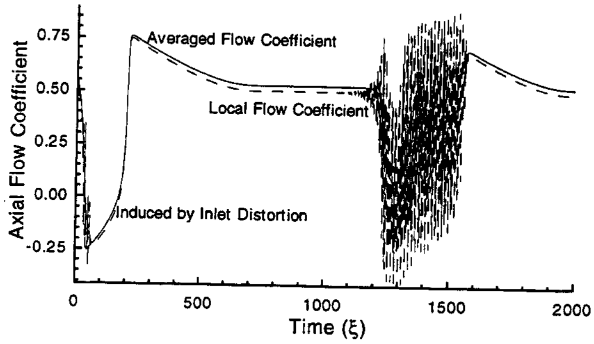


FIG.20 THE TIME HISTORY OF FLOW COEFFICIENT WHEN B=2.6, $\Phi_0$/W=2.35 AND DA=0.1

## The Effect of Compressor Characteristics

It is very important to predict the influence of compressor characteristic on the inception of instabilities in compression systems. Here the effect of compressor characteristic parameters H and W on the inception flow coefficient is analyzed. H and W are the semi-height and semi-width of the axisymmetric compressor characteristic respectively. In reality, however, H represents the loading of the compressor, and W mirrors the level of the design mass flow of the compressor. These results are shown in Fig.21 and Fig.22. With the increase in H the negative slope of compressor characteristic increases at a given flow coefficient. This means that the system is more steady. The result in Fig.21 shows that the inception flow coefficient decreases with the increase in H. Fig.22 shows that with the increase in W, the relative inception flow coefficient decreases initially and then increases.

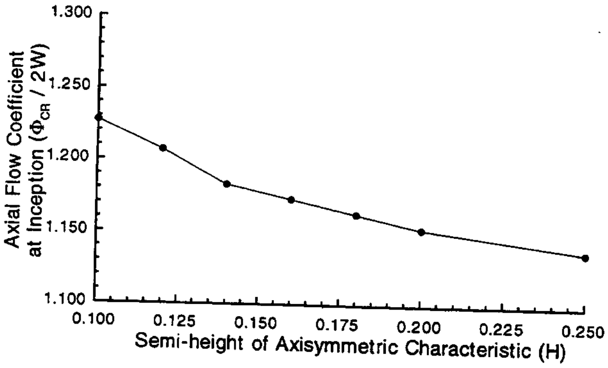


FIG.21 THE EFFECT OF SEMI-HEIGHT (H) OF COMPRESSOR CHARACTERISTIC ON STALL FLOW COEFFICIENT

The results in Fig.23 and Fig.24 show that H and W do not have a strong effect on the propagation speed of rotating stall. They have a significant effect on the stall inception point, but they have little effect on the resonant response frequency, as shown in Fig.25 and Fig.26 respectively.

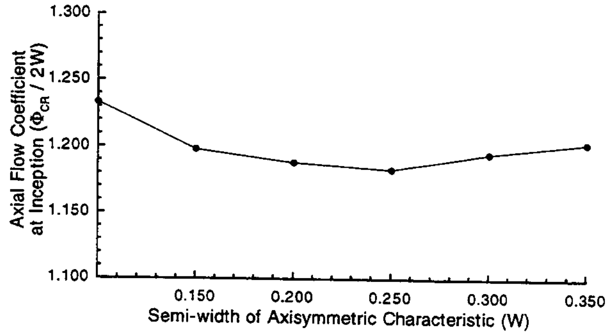


FIG.22 THE EFFECT OF SEMI-WIDTH (W) OF COMPRESSOR CHARACTERISTIC ON STALL FLOW COEFFICIENT

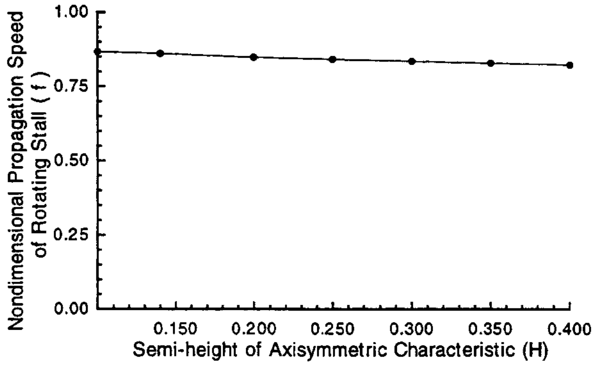


FIG.23 THE EFFECT OF H ON THE PROPAGATION SPEED OF ROTATING STALL

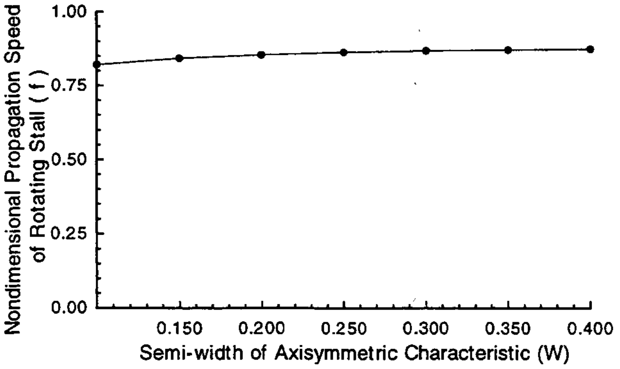


FIG.24 THE EFFECT OF W ON THE PROPAGATION SPEED OF ROTATING STALL

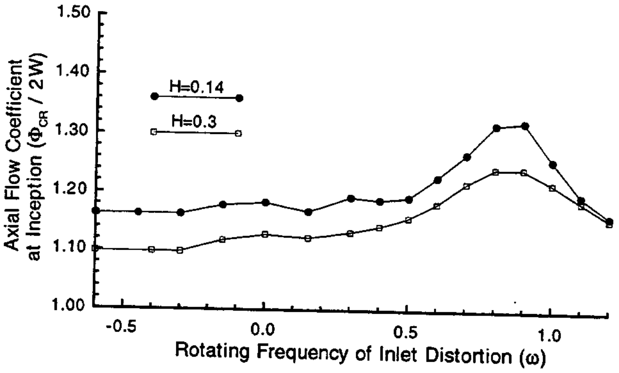


FIG.25 THE EFFECT OF H ON THE RESONANT RESPONSE FREQUENCY

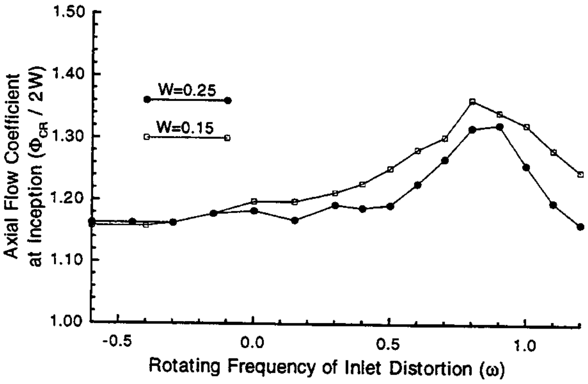


FIG.26 THE EFFECT OF W ON THE RESONANT RESPONSE FREQUENCY

## CONCLUSIONS

(1) Inlet distortion degrades the stability margin of compression systems and has a strong effect on the post stall transient behavior. Under the influence of inlet distortion, initial disturbance develops into fully developed rotating stall very quickly and fully developed rotating stall waves are not steady.

(2) The rotating speed of inlet distortion has a significant effect on the post stall transient behavior and the inception point of rotating stall. The co-rotation may degrade the stability margin of compression systems remarkably, but counter-rotation has a less deleterious effect than co-rotation.

(3) The resonant response frequency, i.e., the rotating frequency of inlet distortion at which the degradation of stability margin is quite large, is close to the natural propagation speed of rotating stall of the system.

(4) The rotating speed of inlet distortion has a similar effect on the boundary of surge as on the boundary of rotating stall.

(5) Parameter B has a strong effect on the inception flow coefficient of rotating stall, but it has no effect on the inception flow coefficient of surge for the case with inlet distortion.

(6) Compressor characteristic parameters have a strong effect on the inception point of instability in compression systems, but they have little effect on the propagation speed of rotating stall and the resonant response frequency.

(7) The rotating speed of inlet distortion has little effect on the propagation speed of rotating stall.
(8) The reciprocal time-lag parameter of blade passage has a strong effect on the propagation speed of rotating stall. The propagation speed increases with the decrease in $\alpha$.
(9) The calculation results are consistent with the available test data.

## ACKNOWLEDGMENTS

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