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A Theory for Predicting Stall Cell Transient Behavior

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ABSTRACT: In this paper, a new model is developed for rotating stall in low speed axial compressors and fans. The theory is developed from Moore's theory. The modified model makes it possible to predict the transient behavior of the stall cells, which is not possible with Moore's theory. The general assumptions such as the layout of the compression system, the lags in the entrance and exit ducts, and the small disturbances are assumed to be similar to those of Moore's theory. However, a second order hysteresis is used in the current work for the pressure rise of the rotor and stator rows. Comparing the experimental results with the theory shows that the modified model can predict the transient behavior of the stall cells fairly accurately. Furthermore, the current model makes it possible to study the effects of different parameters such as the stagger angle, number of stages, and number of stall cells. It has been suggested in the current study that the number of stall cells should reduce to one in a fully developed rotating stall pattern.

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1- Introduction

The operating range of a compressor is limited by the onset of two aerodynamic instabilities, the so-called surge, and rotating stall. Surge is a system instability which includes large amplitude oscillations of the annulus flow through the entire compression system. However, a rotating stall is a localized disturbance which might be limited to one or some of the compressor stages. Theoretical and semi-empirical models of the surge and rotating stall have been reported by a number of researchers [1-5]. Moore [1] developed a model of unsteady pressure rise across a blade passage at in-stall conditions. The stall cell was modeled as a small circumferential disturbance to axial and tangential velocities. The disturbances were assumed to be expressed as Fourier series and the propagation velocity of the stall cell was calculated by equating the coefficients of trigonometric functions.

The main objective of the current study is to develop a modified method based on the basic Moore model [1]. A second order hysteresis is assumed for the pressure rise of the rotor and stator rows, which gives the modified model new capabilities such as investigating the transient behavior of the stall cell (i.e., its transient speed and acceleration which cannot be modeled in the basic Moore model). This is very useful because obtaining similar information from experiments or Computational Fluid Dynamic (CFD) is extremely expensive and challenging.

2- Methodology

2- 1- Modeling

The compression system model is shown in Fig. 1. The compressor is assumed to have N stages as well as Inlet Guide Vane (IGV) and Outlet Guide Vane (OGV). The downstream reservoir is assumed to be large enough to keep the flow uniform.

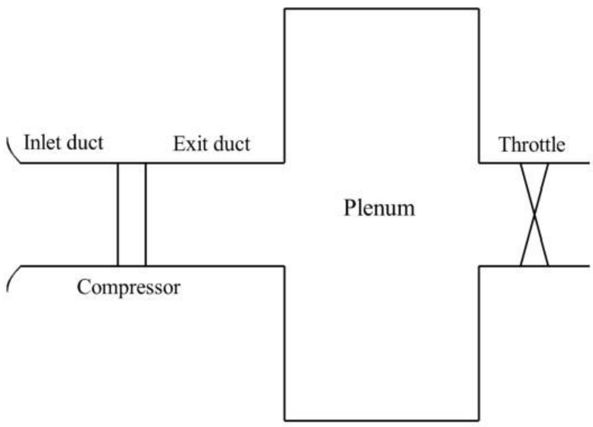

Fig. 1. Compression system model

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Table 1. Compressor specifications (Jackson [9])

	Rotor	Stator
Solidity	1.43	1.1
Chord (mm)	110	114.6
No. of IGVs	0	
Tip diameter (mm)	1524	
Hub/Tip ratio	0.7	
Speed of Rot. (rpm)	500	

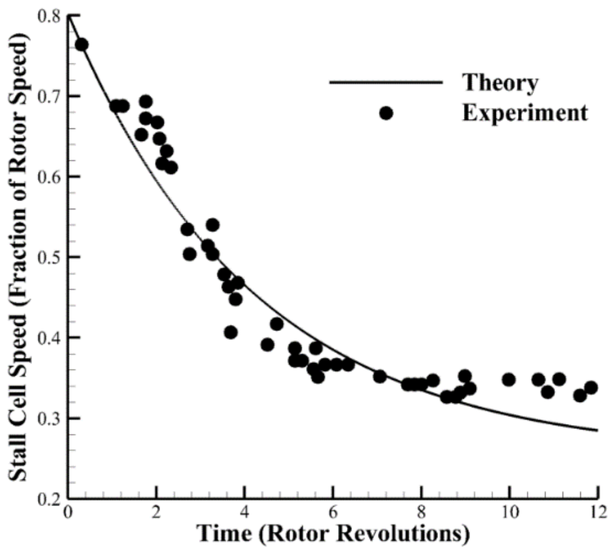

Fig. 2. Comparison between theory and experimental results

The compressor is assumed to have high hub to tip radius ratio blades, which enables a 2-D flow assumption. The inlet and outlet channels as well as the compressor are assumed to have constant cross-sections. The flow is assumed to be incompressible, frictionless and irrotational at the entrance of the compression system, and therefore, the Laplace equation can be applied.

In the recent works reported by Shahriyari et al. [6, 8] and Khaleghi et al. [7], the compressor pressure rise function used by Moore [1] was modified to include a second order derivative term. The same hypothesized function is used in the current study:

$$\frac{\Delta p}{\frac{1}{2}\rho U^2} = F(\varphi) - \tau(\varphi)\left(\frac{d\varphi}{dt} + \frac{d^2\varphi}{dt^2}\right) \quad (1)$$

In this equation, τ is the hysteresis parameter,   is the flow coefficient and t is the time. The final speed of the stall cell is

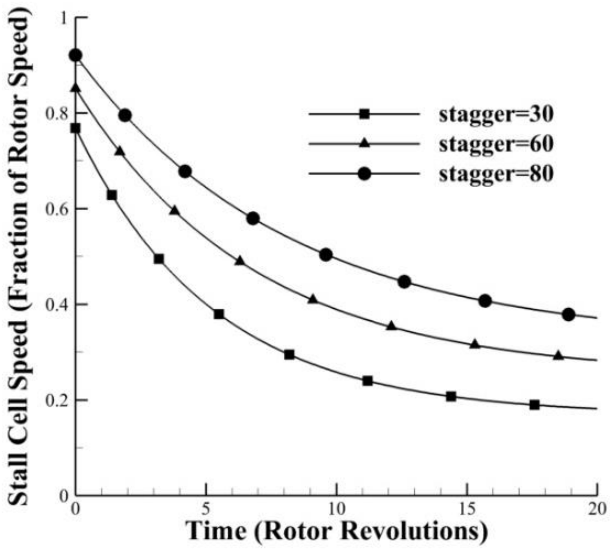

Fig. 3. Effect of stagger angle on the speed of the stall cell

obtained as follows:

$$f = \frac{\frac{1}{2}}{1+\frac{m}{k}\left(\cos^2\gamma\right)\frac{1}{2n}\frac{D}{2nL}+\frac{1}{2N}\left(1+\cos^2\gamma\right)} + C\exp\left(-t\left(1+\frac{D\cos^2\gamma}{2nL\frac{k}{m}\left(2N+\left(1+\cos^2\gamma\right)\right)}\right)\right) \quad (2)$$

Where C is the integral constant, D is the mid compressor diameter, L is the axial length of a row in the axial direction, m is the compressor outside lag, n is the number of stall cells, N is the number of compressor stage, k is the internal compressor lag and   is the stagger angle. Note that the integral constant (C) shall be determined from experimental data.

The first term in Eq. (2) is the final (steady) speed of the stall cell in a fully developed rotating stall pattern, which was obtained in Moore [1]. The second term (the time dependent term which is of the exponential form), however, is the transient speed of the stall cell.

2- 2- Validation

In order to explore the ability of the modified model developed in the current study in predicting the transient stall cell speed, the experimental results reported by Jackson [9] are compared to the theory in Fig. 2. The compressor specifications are given in Table 1. It should be noted that C is chosen to be 0.6, because it gives the same initial cell speed that Jackson measured (roughly 0.8 as can be observed in Fig. 2). As shown in Fig. 2, the theory can predict the transient speed of the stall cell quite accurately.

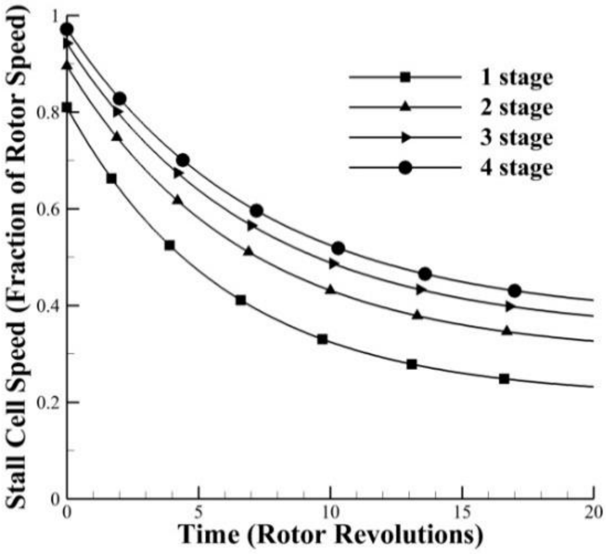

Fig. 4. Effect of number of stages on the speed of the stall cell

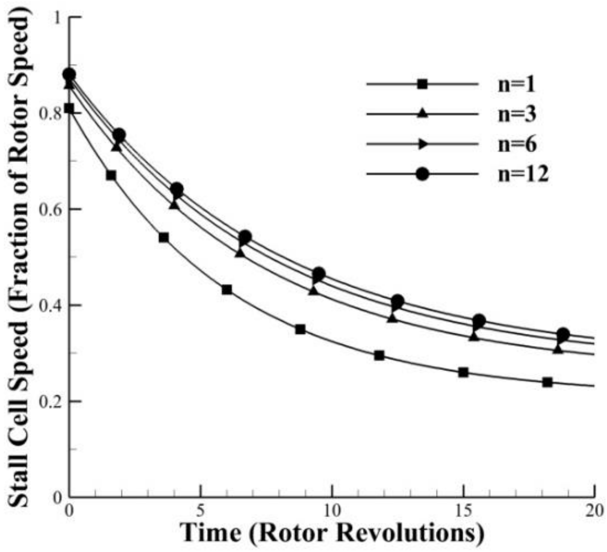

Fig. 5. Effect of the number of stall cells on their speed

Results and Discussion

2- 3- Effect of stagger angle

Eq. (2) shows that the final (steady-state) speed of the stall cell increases by increasing the stagger angle of the blades. In order to investigate the effect of the stagger angle on the cell speed, Eq. (2) was solved for various stagger angles while keeping other parameters the same. Note that the test case is the Jackson compressor with the specifications given in Table 1. Furthermore, it should be mentioned that the number of the stall cells (n) is chosen to be one. Fig. 3 shows the speed of the stall cell for a period of 20 rotor revolutions. Three cases having stagger angles equivalent to 30, 60, and 80 degrees are plotted in this figure. As shown in Fig. 3, increasing the stagger angle considerably increases both the initial and final speeds of the stall cell (by changing the stagger angle from 30 to 80 degrees, the final cell speed increases from 0.182 to 0.371).

2- 4- Effect of number of stages

Fig. 4 shows the speed and acceleration of the stall cell for a different number of stages (other parameters are kept the same). Similar to the stagger angle, the number of the stall cells is chosen to be equivalent to one. As this figure shows, increasing the number of the compressor stages causes greater initial and final speeds of the stall cell.

2- 5- Effect of number of stall cells

The number of stall cells affects their speed, as indicated by Eq. (2) and shown in Fig. 5. It is shown that the more the number of stall cells, the greater their initial and final speed.

3- Conclusions

A modified theory of rotating stall in axial flow compressors has been presented. The theory has been developed from Moore's theory. The general assumptions such as the layout of the compression system, the lags in the entrance and exit ducts, and the small disturbances were assumed to be similar to those of Moore's theory. However, a second order hysteresis has been used in the current work for the pressure rise of the rotor and stator rows. Comparing the experimental results with the theory showed that the modified model can predict the speed of the stall cell fairly accurately. Results showed that increasing the stagger angle of the blades and the number of compressor stages increases the initial and final speed of the stall cells. The theory further suggested that in a fully developed rotating stall pattern, the number of stall cells should reduce to one.

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