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.

KEYWORDS

Rotating stall, Stall cell speed, Axial compressor, Moore's theory

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, rotating stall is a localized disturbance which might be limited to one or some of the compressor stages. Theoretical and semi-empirical models of 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 condition. 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 experiment or CFD (Computational Fluid Dynamic) is extremely expensive and challenging.

Modeling

The compression system model is shown is Figure 1. The compressor is assumed to have N stages as well as IGV and OGV. The downstream reservoir is assumed to be large enough to keep the flow uniform.

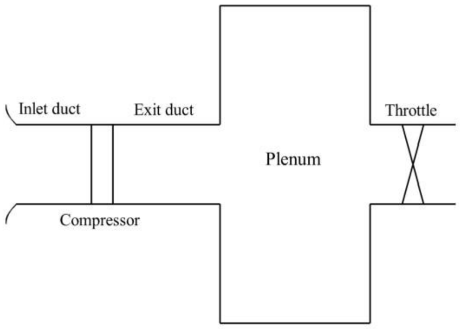

Figure 1. Compression system model

The compressor is assumed to have high hub to tip radius ratio blades, which enables 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, 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:

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

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

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

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

The first term in Equation 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 exponential form), however, is the transient speed of stall cell.

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 Figure 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 Figure 2). As shown in Figure 2, the theory can predict the transient speed of the stall cell quite accurately.

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	

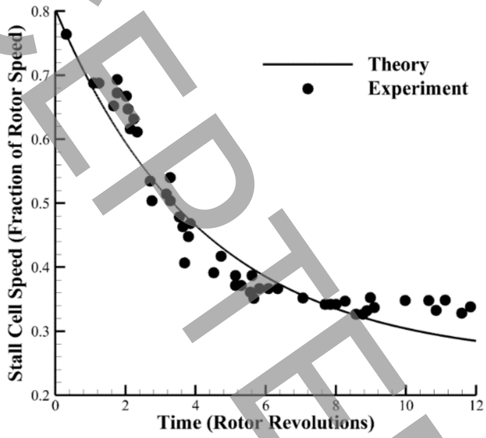

Figure 2. Comparison between theory and experimental results

Effect of stagger angle

Equation 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, Equation 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. Figure 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 Figure 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).

Effect of number of stages

Figure 4 shows the speed and acceleration of the stall cell for 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.

Effect of number of stall cells

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

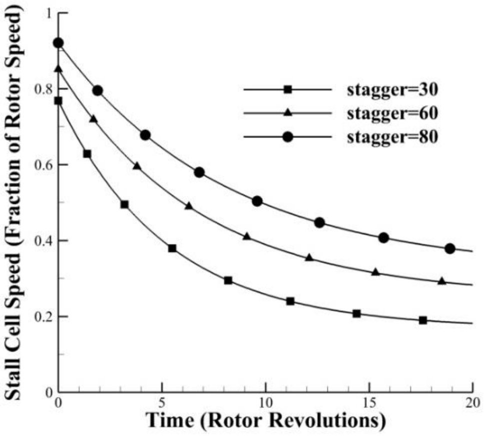

Figure 3. Effect of stagger angle on the speed of the stall cell

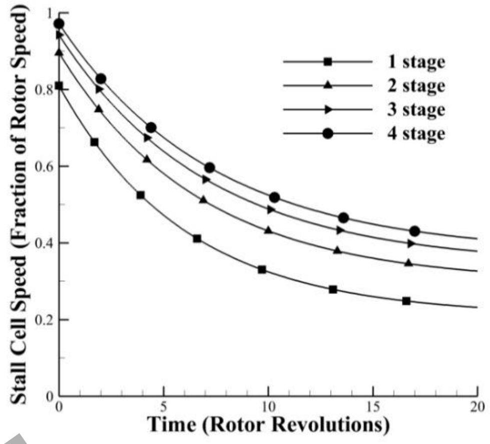

Figure 4. Effect of number of stages on the speed of the stall cell

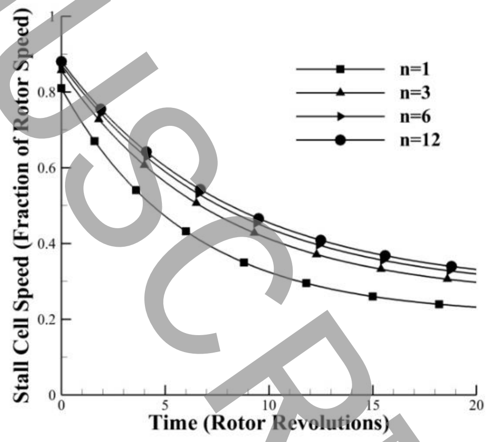

Figure 5. Effect of the number of stall cells on their speed

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 increase 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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