DISCUSSION

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Dr. Moore is to be complimented on this contribution to the understanding of the performance characteristics of multistage compressors operating in rotating stall. The insight gained as to the interaction of the compressor's pumping characteristic with the inlet and discharge flow fields presents a convenient arena within which specific elements of the model can be scrutinized. This discussion is intended to support (and emphasize) Dr. Moore's concluding remark that research is needed on entrance flow fields.

Through the cooperation of Dr. E. M. Greitzer at the Massachusetts Institute of Technology, the FORTRAN coding for a numerical solution of Dr. Moore's model was made available to United Technologies Corporation, Pratt & Whitney Aircraft (P&WA). Automated iteration routines were added and the program was streamlined by P&WA to allow the "cause and effect" relationships of the model to be thoroughly investigated in a relatively short time. The test case to be considered here involved the $\phi^* = 1.0$, three-stage configuration from Day's disseration ([6], Part III). Figure 17 shows the axisymmetric pumping characteristic, ψ_c, that was selected for this study. (The positively sloped portion of the characteristic is an arbitrary straight-line connection between the unstalled (data) characteristic and a reverse flow characteristic based on an analytical prediction.) Also shown on this figure is the measured characteristic in rotating stall, Ψ, and the value of Ψ calculated by the model at $\Phi = 0.3$. (This Φ was chosen because Day's dissertation includes detailed time-averaged measurements at this flow.) As Dr. Moore has previously noted, the agreement in the Ψ level is poor.

The crux of the problem appears to be directly related to the basic nature of the flow field prediction; specifically, the prediction of the Cx/U profile, $\phi(\theta)$. A comparison of the predicted and measured $\phi(\theta)$ profiles is shown in Fig. 18. (The angular alignment is arbitrary.) Outwardly, the comparison looks good, but upon closer examination, one realizes that the major portion of the cycle is made up of nearly linear excursions of the negatively sloped portions of the unstalled and backflow ψ_c characteristics, with the transitions between these characteristics being quite abrupt. The data, on the other hand, suggest a more "cellular" or "parallel compressor" distribution. This predicted ϕ profile will necessarily result in a ψ_c profile versus θ such as shown in Fig. 19. The basic pressure rise equation (Moore's equation (3.1) gives

$$\Psi = \frac{1}{2\pi}\int_0^{2\pi} (\psi_c(\phi) + mfh(\theta) - \lambda g'(\theta))\,d\theta$$

$$= \frac{1}{2\pi}\int_0^{2\pi} \psi_c(\phi)\,d\theta$$

since the integrals of $h(\theta)$ and $g'(\theta)$ over a cycle must be zero. In applying this equation to the profile of Fig. 19, one notes first that ψ_c varies nearly linearly with θ over the unstalled and backflow characteristics and, second, that the transition regions contribute very little to the integral (thus suggesting that the exact shape of ψ_c between the stable unstalled and backflow legs probably is of secondary importance). This will result in a prediction of

$$\Psi \approx \tfrac{1}{2}(\psi_{c_{\max}} + \psi_{c_{\min}})$$

in all cases, and the data do not generally support this result.

In our evaluation of the model, input parameters were systematically varied in an attempt to alter the basic shape of

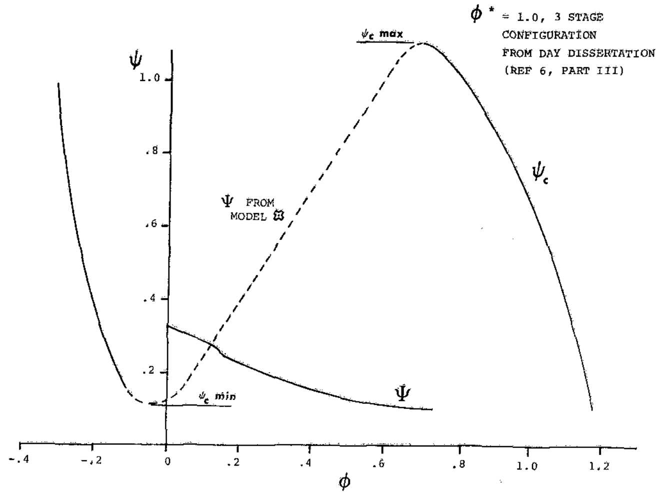

Fig. 17 Axisymmetric pumping characteristic

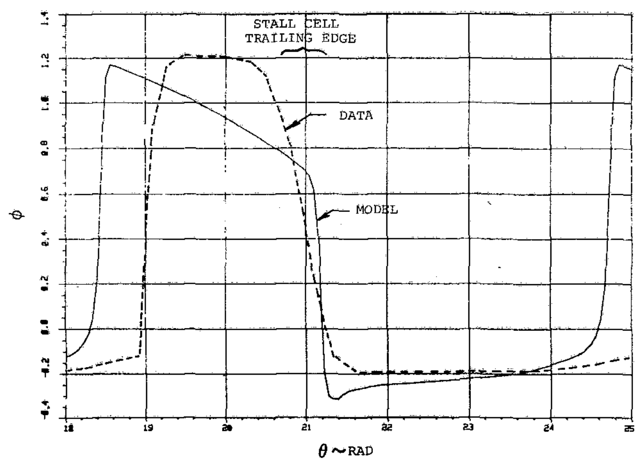

Fig. 18 Comparison of predicted inlet Cx/U profile with data

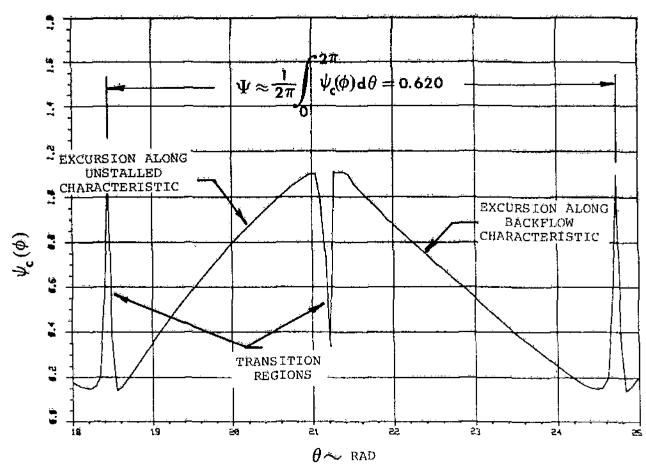

Fig. 19 Variation in pumping profile over a stall cycle

the calculated ϕ profile. This was not successful, however, as none of the variables seemed to exert a first-order effect. An example is shown in Fig. 20, where the compressor lag parameter λ was both halved and doubled. The external lag parameter, m, was varied from 2.0 to 1.5 with the only effect being a steepening of the transition regions. Otherwise the shape of the ϕ profile was unchanged.

Toward understanding why the predicted ϕ profile exhibits

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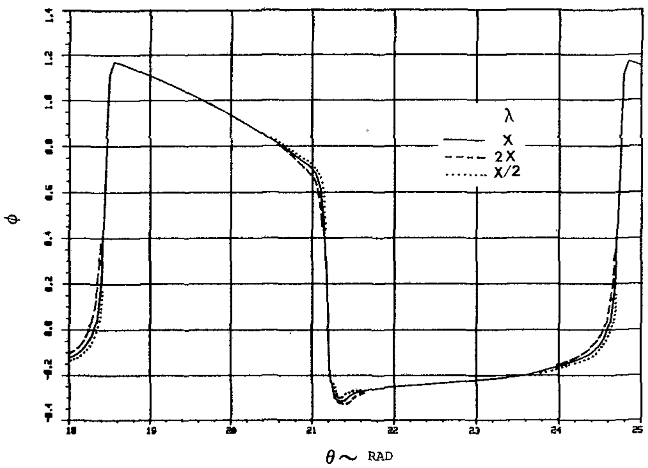

Fig. 20 Effect of compressor lag term

this unalterable shape, it is suggested that the problem may lie in the assumption of potential flow in the upstream channel. Recent post-stall data obtained at P&WA have shown that considerable backflow exists in the stalled cell, and this backflow can extend upstream as far as a compressor diameter or so. It is difficult to imagine that the interaction of this backflow with the incoming (net) flow would be potential, i.e., irrotational. Compounding the problem is the lack of experimental data—understandable in light of the difficulty involved in obtaining such measurements—from which one could deduce a more suitable representation.

At any rate, it appears as if the accuracy of the model, at least as far as the Ψ prediction is concerned, depends almost entirely on the shape of the ϕ profile. This is an important observation, since it allows one to properly focus future studies.

Author's Closure

I am grateful to Mr. Lewis for his interest and appreciate very much the useful contribution he has made in providing the foregoing very informative discussion.

Understanding, now lacking, of entrance and exit flows with reversal is badly needed for further progress in the study of rotating stall, and I believe Mr. Lewis is quite correct in emphasizing that Day's Case IV [3] must involve reverse-flow considerations that are not included in the theory. It may be helpful to remark that Case IV is quite peculiar in its very low value of Ψ in deep stall; Case II (Fig. 15 of the present paper) shows a rising characteristic in deep stall and agrees well with the theory. Which behavior is more typical? Perhaps, as Fig. 23 of [3] suggests, the rising type is at least very common among axial compressors.

In terms of the present theory, one might say that Case IV behaves as if the reverse-flow resistance were very low; if that were true, the predicted limit cycle would be of the type shown by the symbol Δ ($\beta = 0.25$) in Fig. 6, which is not "caught" by the reverse-flow leg of the diagram. One result would be that δ would be nearly zero, so that the deep-stall Ψ could indeed remain low, as in Case IV. Case IV has a very low stagger angle (20 deg), and it seems conceivable that a low resistance to reverse flow is implied.

Mr. Lewis and I differ somewhat in our views of the importance of the axial profile. I feel that the profile should be just one of the results of a theory, along with pressure rise (Ψ), propagation speed, and recovery point. In none of those features does the theory successfully predict Case IV! It would be interesting to see how the axial profile, calculated by Mr. Lewis's method, would compare with experiment for Case II, for which theory seems more successful in other respects.