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Design Geometry and Design/Off-Design Performance Computer Codes for Compressors and Turbines

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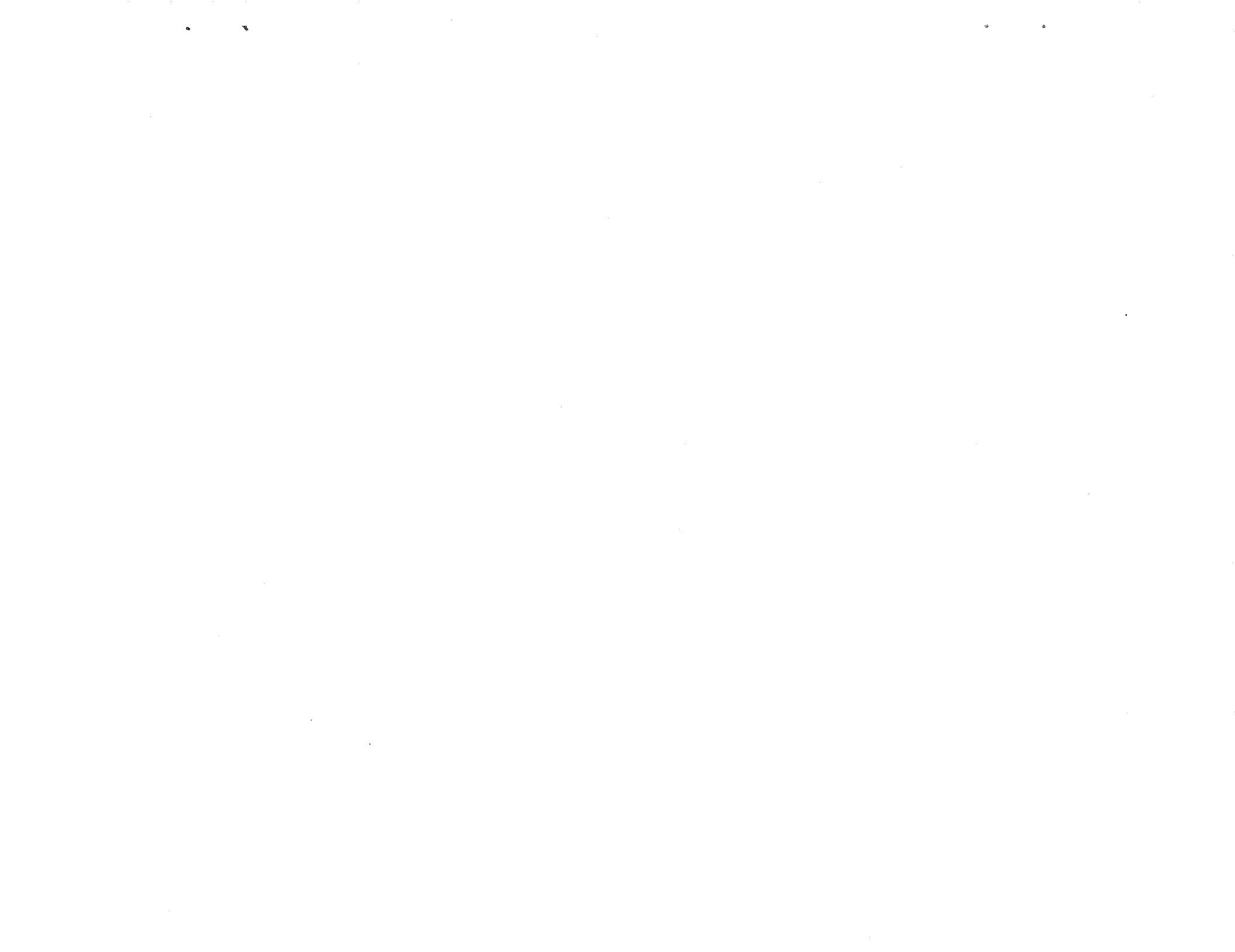


**Design Geometry and Design/Off-Design Performance
Computer Codes for Compressors and Turbines**

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ABSTRACT

This report summarizes some NASA Lewis (i.e., government owned) computer codes capable of being used for airbreathing propulsion system studies to determine the design geometry and to predict the design/off-design performance of compressors and turbines. These are not CFD codes; velocity-diagram energy and continuity computations are performed fore and aft of the blade rows using meanline, spanline, or streamline analyses. Losses are provided by empirical methods. Both axial-flow and radial-flow configurations are included.



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SUMMARY

This report summarizes some NASA Lewis (i.e., government owned) computer codes for the determination of design geometry and the prediction of design/off-design performance of compressors and turbines. Not all such codes available at NASA Lewis are presented, but those included provide the conceptual/preliminary design capabilities required for airbreathing propulsion system studies. Both axial-flow and radial-flow configurations can be analyzed. Under Grant NAG3-1165, ten of these existing operational codes were gathered, evaluated, modified as deemed necessary/desirable, and documented to report significant changes. In addition, two codes of a research nature are included as potential for enhanced capabilities.

These are not CFD codes. Velocity-diagram energy and continuity computations are performed fore and aft of the blade rows using meanline, spanline, or streamline analysis techniques. Losses are provided by empirical correlations or by simple physics with empirical coefficients. These programs run very fast; answers are obtained in seconds on a UNIX workstation, and many of the codes run on a PC in a matter of minutes or less. Most of the codes are quite robust in terms of running to completion.

It must be remembered that these codes are merely tools to be used by the analyst. They cannot differentiate between acceptable and unacceptable design/performance solutions as long as these solutions are mathematically feasible. The user must contribute some knowledge to the process of selecting a best, or even an acceptable, design.

INTRODUCTION

Performing preliminary studies of gas-turbine power or propulsion systems requires the capability to rapidly produce conceptual designs of the compressors and turbines in order to determine geometry, design-point performance, and off-design performance. The typical turbomachine "design" code enables a study of the interrelationship of the number of stages, the flowpath dimensions, the gas velocities and flow angles, and the resultant variation in design efficiency. The "off-design" code can then provide the interrelationship of efficiency, flow, pressure ratio, and speed (i.e., the map) for each geometry of interest.

Over the past 30 years, NASA Lewis has developed, both inhouse and under contract,

numerous computer programs that perform the design and the off-design analyses for compressors and turbines of both the axial-flow and the radial-flow (i.e., centrifugal compressor and radial-inflow turbine) types. Conservation of mass and energy computations are performed fore (i.e., in front of) and aft (i.e., behind) of each blade row. Losses across the blade rows are modeled by empirical methods. The analyses, depending on the particular code, use meanline, spanline (constant span fraction), or streamline (constant flow) methods. This type of analysis is very rapid as compared to CFD computations.

This report describes in summary fashion codes that, under Grant NAG3-1165, have been gathered together, evaluated, modified and documented as needed, and made available for airbreathing propulsion system studies at the NASA Lewis Research Center. Design and off-design analyses for both axial-flow and radial-flow compressors and turbines are included.

SELECTION OF CODES

To enhance the fidelity of airbreathing propulsion system studies at the NASA Lewis Research Center, it was desired to incorporate turbomachinery geometry and performance analyses into the study process. The turbomachinery analysis would be included in the engine study process as shown in figure 1. Cycle and flowpath analyses initially produce a preliminary engine flowpath and compressor/turbine design requirements. Compressor and turbine design and off-design analyses are then used to adjust the flowpaths and numbers of stages and determine blade counts, blading parameters, and design/off-design performances, all of which are iterated back into the cycle and flowpath analyses until closure is reached.

Historically, compressors and turbines are analyzed using different codes, axial-flow and radial-flow configurations are analyzed with different codes, and design and off-design analyses are performed with different codes. Thus, we have the need for 8 codes without even considering variations due to the tradeoff between modeling fidelity and code complexity.

The only readily available turbomachinery design and off-design codes are those that are government owned, most of which were developed by Lewis Research Center inhouse or contract efforts. Since I was personally involved with the development of most of the turbine codes, and being somewhat familiar with what my colleagues at the other end of the shaft were using, I pretty well knew what was available in the way of design and off-design codes. A search of the COSMIC (Computer Software Management and Information Center) catalog provided a few additional candidates.

For most of the categories, there was no choice to be made since only one code of that type appeared to be available. In a couple of cases where essentially similar codes were available from alternate sources, codes that were previously or currently in use at Lewis Research Center were favored. In only one instance was a code (axial compressor spanline design) imported from outside Lewis; and it turned out that particular code had been developed for Lewis but never used there due to an inhouse code of greater capability (but more complexity) developed at about the same time.

In the sections to follow, the selected codes for each of the categories are referenced and briefly described. In only two categories were more than one existing code selected to provide simplicity versus complexity: spanline and streamline axial compressor design codes and meanline and streamline axial turbine design codes. Published documentation is available for 8 of the 10 codes. Unpublished user documentation plus some published background is available for the other 2 (centrifugal compressor) codes. Two additional codes were explored to simplify axial compressor meanline off-design analysis; these must be treated as "research" codes requiring modification/calibration of some of the modeling. User documentation for these 12 codes were gathered together as an unpublished loose-leaf "Users Manual" (ref. 1) with distribution limited to Lewis Research Center.

COMPRESSORS

The axial-flow compressor and the centrifugal compressor design and off-design codes are presented in this section.

Axial-Flow

Two design codes and 3 off-design codes are discussed for axial-flow compressors. The streamline design code ACD provides more capability and potential accuracy than does the spanline design code CSPAN, but at the cost of considerably more input and more difficulty in obtaining solutions for advanced transonic compressors. The streamline off-design code ACOD is a companion to the ACD code and poses similar, but more severe, difficulties. The two meanline off-design codes CMPSTK and OFFDES were attempts to simplify the off-design analysis, but additional work with the modeling is required before either of these codes can be used with any confidence.

Design Codes.- **CSPAN** (refs. 2 - 5) is a spanline analysis code that uses isentropic simple radial equilibrium to determine the flowpath and efficiency either for a given number of stages or for a given overall pressure ratio. There is only one calculation station between blade rows. Hub radius is determined from the inlet radius ratio and the input tip radius distribution; this simplifies the continuity solution. Stage energy addition is controlled by specifying maximum allowable values for several aerodynamic design parameters: rotor-tip and stator-hub diffusion factors, rotor-hub turning, and stator-inlet-hub Mach number. There are two internal loss models: (1) stage and rotor polytropic efficiencies as functions of stage pressure ratio, and (2) blade-row pressure-loss coefficient as a function of meanline diffusion, endwall clearance, and shocks. Correlations are included for the calculation of endwall blockage (optional) and for the prediction of stall margin.

CSPAN input includes the design requirements of flow rate and overall pressure ratio (or maximum number of stages). First-rotor tip speed, inlet radius ratio, tip-diameter variation, and aerodynamic design limits can be fixed or varied for parametric studies. Default values are available for the aerodynamic limits as well as for solidities, aspect ratios, and stage reaction distribution. The output includes the hub radii, diagram velocities and angles, blading geometry, stage and overall efficiencies, and stall margin. CSPAN can produce a complete input file for the meanline off-design code OFFDES. This code is quite robust,

especially with free-vortex radial distributions.

ACD (aka CDC) (refs. 6 and 7) is a streamline analysis code with full radial equilibrium based on spline-fit curves to determine streamline slopes and curvatures. The aerodynamic solution gives velocity diagrams on the streamlines at (i.e., outside) the blade-row edges; thus, there are at least two stations between blade rows (additional annular stations are allowed). Since tip and hub radii are both specified, the continuity and energy solutions are more closely (as compared to CSPAN) related resulting in a much greater possibility of an unacceptable solution or none at all; however, this allows ACD to model any given flowpath. Stage energy addition is here too controlled by specifying limits for several aerodynamic parameters; this code, however, can transfer work from stages that exceed their limits to those that are under their limits. Blade elements are defined by a polynomial centerline curve and a polynomial thickness distribution; this gives a great deal of flexibility, but requires expertise to produce anything beyond circular arcs. The blade-element inlet and outlet angles are established through either tabular input or empirical correlations for incidence and deviation angle adjustments to the velocity diagrams. Blade-element pressure-loss coefficients are specified either by tabular input or an internal correlation (ref. 3) added during the course of this effort. Shock losses are separately computed. The blade elements can be stacked to give the full blade design.

ACD input includes the annulus profile, the mass flow, the inlet conditions, the pressure ratio, and the rotative speed. A number of parameters and polynomial coefficients are input to specify and control the blade-row aerodynamics and geometry. Input files are relatively large; even with the simplest options, the input file is more than an order of magnitude larger than that required for CSPAN. The output from the aerodynamic solution has an overall performance summary, which can optionally be followed by the aerodynamic and geometric blade-element parameters for the individual blade rows. If desired, streamwise blade coordinates for internal flow analysis codes and/or coordinates on plane sections through blades for fabrication drawings can be output. Also, an input file for the streamline off-design code ACOD can be optionally produced. With free-vortex radial distributions and subsonic aerodynamics, the ACD code generally runs well. For transonic aerodynamics, finding a solution within the constrained flowpath could become a bit more troublesome. Moving away from free vortex requires expertise with any code.

If ACD is run with all the easy-to-use options, then the solution is really no better than that from CSPAN except that a design solution with a smooth specified hub profile is obtained. To really benefit from all the capabilities of ACD requires an experienced knowledgeable user.

Off-Design Codes. - **ACOD** (aka COFFD) (ref. 8) is a streamline analysis code for computing the off-design performance of multistage axial-flow compressors. It is a companion code to the streamline design code ACD in that it was developed by the same person (James Crouse) and the geometry, flow, and loss modeling are similar to that described above for ACD. The same pressure-loss coefficient correlation added to ACD was also added to ACOD. This code does not by itself find stall or choke, but it does recognize when it is choked. You can sneak up on choke, but it takes the judgement of the user to estimate the stall point on each speed line.

The ACOD input requires the annulus profile and the blading angles and profiles on all the streamlines. The input files are large; a 3-stage compressor requires about 200 lines and the size grows proportionately with number of stages. However, the ACD design code can produce an input file for ACOD. As with ACD, a low-speed lightly-loaded compressor can be analyzed by ACOD without much difficulty. For high-speed transonic multistage machines, it becomes extremely difficult to even reproduce the design point, let alone compute performance at off-design points. Code failure is accompanied by the printing of some internal variables or, often, by no message at all. An expert user is definitely required for this code.

Two approaches were attempted to simplify the prediction of axial-compressor off-design performance. This resulted in the CMPSTK code and the OFFDES code, both of which are documented only in reference 1. Both of these are considered to be "research" codes in that the modeling has not been developed to the stage of producing consistently reliable results.

CMPSTK is a combination of STGSTK (ref. 9) and CMPGEN (ref. 10). STGSTK is a computer code for predicting multistage axial-flow compressor off-design performance by a meanline stage-stacking method. The individual stage characteristics (pressure coefficient and efficiency versus flow coefficient) are either input or internally derived from design-point performance. Either way, the flow range between stall and choke at design speed must be known for each stage, as well as the ratio of maximum efficiency at each speed to that at design speed. STGSTK then modifies the stage characteristics for off-design speeds as well as for blade reset, and thus computes off-design performance, including the effects of variable geometry, with a meanline calculation based on the modified characteristics.

For the early phases of a system study, neither the design-speed flow range nor the efficiency ratios are known for the individual stages. Estimates for these, however, can be provided by CMPGEN, which is an axial compressor map generator based on empirical characteristics related to overall performance requirements. Thus, the combination of STGSTK and CMPGEN yields a potential capability to compute off-design performance without prior knowledge of individual stage characteristics. While the map itself is probably no better than that generated by CMPGEN alone, a capability to study variable-geometry effects is obtained.

Required geometry inputs for CMPSTK are the inlet and exit tip and hub diameters, design inlet absolute flow angle, inlet blade angle, and solidity for each rotor row. The minimum input required to establish the stage characteristics are the design pressure and the design efficiency for each stage. Stator and/or rotor blading resets can be specified. Stall margin and choke margin inputs can be used to adjust the stage characteristics as needed. The output presents the multistage compressor performance from stall to choke at specified speeds provided that the stage characteristics are properly matched. CMPSTK is very reliable with regard to running to completion. However, some degree of varying the inputs, particularly those affecting stage flow range/matching, will most likely be needed to obtain usable results.

OFFDES is a meanline blade-row-stacking flow and energy conservation calculation for

pressure ratio and efficiency as functions of flow and speed. The off-design loss and deviation models are those of references 11 and 12. The inlet and exit of each blade row are checked for choking with simple continuity models. There is no calculation made for the prediction of stall; however, a comparison of code calculations with stage data indicates that the code's stalling incidence correlation or a maximum blade-row density-rise ratio (as used in ref. 11) may be able to be used to predict stall, at least to some degree. The endwall blockage calculation described in reference 12 is available as an option.

The OFFDES input requires the annulus radii at each blade row inlet and exit, the blading inlet and exit angles, and the design loss coefficients, incidence, and deviation. A complete input file can be written by the CSPAN design code. OFFDES is currently terminal driven and will run only one point at a time; since it is considered to be a "research" code, the running of an entire speed line from stall to choke has not been automated. Overall performance is written to the terminal, and complete detailed output for each point run is sent to a file.

OFFDES runs very robustly to completion, especially if endwall blockage is not computed. The pressure ratio-flow characteristics over a range of speeds compare reasonably well with data for the few cases run. Modeling of the losses along the speed lines requires further evaluation and modification/calibration. Stage matching, especially for high-speed transonic compressors, also needs further evaluation. The off-design performance prediction for multistage axial-flow compressors is undoubtedly the most difficult calculation of all those covered in this report. With further efforts by someone who understands compressor behavior, the OFFDES code can perhaps be turned into a useful tool for conceptual studies.

Centrifugal

The CCD design code and CCOD off-design code are a matched set produced by the same original and current developers.

Design Code. - **CCD** (aka QUIK) (refs. 13 and 14) provides a rapid preliminary assessment of design geometry and design-point performance of centrifugal compressors with radial or swept rotor blades. The analysis is based on a one-dimensional meanline flow model with correlations for the following losses: inlet guide vane; rotor shock, incidence, clearance, blade loading, skin friction, disk friction, and recirculation; vaneless diffuser skin friction; and vaned diffuser friction and loading. Free-vortex prewhirl can be specified, and simple radial equilibrium is used to provide the radial gradients at the rotor inlet. Splitter blades are allowed. Design-point efficiency and stall margin (determined by the off-design code), whose requirements are usually at odds with each other, are largely determined by impeller-inlet flow angle and diffuser throat area. Choke margins are used to control these parameters. CCD can operate in design mode with input flow and pressure ratio or in analysis mode with input geometry.

For design mode, the program input includes mass flow rate and pressure ratio. The key design variables are inlet flow angle and velocity; rotor rotational or specific speed, exit blade angle, and reaction; and amount of diffusion in the vaned (or pipe) diffuser. The output

presents the computed design geometry, efficiency, and local flow parameters. A complete input file for the CCOD off-design code can be written by the CCD design code. This code runs very reliably.

Off-Design Code.- CCOD (aka CCODP) (refs. 15 and 16) is a one-dimensional meanline code for the off-design performance of centrifugal compressors with radial or swept rotor blades. The losses are the same as enumerated above for CCD, as are the capabilities to handle inlet prewhirl and splitter blades. Stall prediction is based on pressure recovery from impeller exit to diffuser throat or on diffuser incidence. Choke may occur at the impeller inducer (i.e., inlet), the impeller exit, or the diffuser throat.

CCOD input includes the flowpath dimensions and the blading angles. The CCD design code can prepare the CCOD input file. Calculations are performed for the desired speeds from low to high flow subject to stall and choke limitations. Each speed line can be run automatically from stall to choke, or just parts of the speed line can be run by specifying inlet velocity-ratio limits. Pressure ratio and efficiency are output as functions of flow and speed, and detailed velocity-diagram output can be optionally presented. A map file in NEPP format (ref. 17) can be obtained. This code also runs very reliably.

TURBINES

The axial-flow turbine and the radial-inflow turbine design and off-design codes are presented in this section.

Axial-Flow

Two design codes and one off-design code are described for axial-flow turbines. The streamline design code TD2 provides more design generality than does the meanline design code TURBAN, but at the expense of more input and sometimes more trouble in obtaining a design solution. The spanline off-design code AXOD can also run as a meanline analysis.

Design Codes.- TURBAN (refs.18 - 20) is a meanline design code based on simplifying assumptions that limit the generality of the analysis but result in a very rapid calculation that needs a minimum of input. This is not the typical blade row by blade row bookkeeping of mass and energy. The stage velocity diagrams are either all similar (thereby having the same work factor) or are determined from an input stage work split. All stages have the same stator-exit angle. Stage by stage tailoring of the velocity diagrams is not allowed. Only inlet and exit diameters are specified, and the stage mean diameters vary linearly. The loss model is a simple viscous type related to the velocity diagrams. The blading model of reference 3 provides solidities and stagger angles. Turbine coolant flows and temperatures can be specified.

TURBAN input includes flow rate, rotative speed, and power or pressure ratio. Options are provided for varying number of stages; diameter (mean or hub or tip); stator-exit angle or exit radius ratio; and reaction, loading, diagram type, and/or work split. The output presents

annulus dimensions, diagram velocities and angles, blading geometries, and efficiencies. TURBAN is very robust and almost never fails to converge to a solution where one exists.

TD2 (refs. 21 - 23) performs a streamline analysis that uses meridional velocity gradients to control the radial distribution of flow and work for the design of multistage, multishaft, cooled or uncooled, axial-flow turbines. Using a specified meridional velocity gradient rather than a specified tangential velocity gradient assures an acceptable flow distribution, thus avoiding a major cause of program failure. Streamline slope and curvature are included in the radial equilibrium. The flowpath radii are fully specified. The velocity diagrams for each stage can be individually controlled. An internal loss correlation determines blade-row total-pressure-loss coefficients along the streamlines.

TD2 input includes primary and coolant flows, temperatures, and pressures; rotative speed, and power. Design parameters that can be varied include number of stages, hub and tip radii streamwise distribution, stage work split, and stage velocity-diagram optional controls such as stator-exit tangential velocity (mean), stator-exit angle radial distribution, and blade-row exit meridional velocity distributions. The output presents the detailed distributions of temperatures, pressures, velocities, and angles, as well as the stage and overall efficiencies.

Code TD2 provides the capability to tailor/control the stagewise as well as the radial variations of the velocity-diagram characteristics, but requires considerably more input than does TURBAN. Any turbine of known flowpath and velocity-diagram design can be modeled. This capability allows the user to go beyond the conceptual study into a preliminary design and also to evaluate specific configurations. Due to the need to satisfy many constraints at once (continuity within the given flowpath, stage work, radial equilibrium, the blade-element loss correlation, radial distribution of stator-exit angle or meridional-velocity, and radial distribution rotor-exit work or meridional-velocity gradient), it is not unusual to find combinations of inputs for which no solution exists. This type of failure can be minimized by maintaining the radial distributions close to free vortex values and allowing ample flow area.

Off-Design Code.- **AXOD** (refs. 24 and 25) is a spanline (which can be reduced to meanline as a lower limit) analysis code with simple radial equilibrium to compute the flow and efficiency of multistage axial-flow turbines as functions of speed and pressure ratio. Although this is basically a spanline analysis, interpolation procedures are used to account for flow entering and leaving the constant sectors within blade rows. Each speed line can be run from low pressure ratio up to the maximum pressure ratio of limit load. The loss model is made up of blade-row inlet losses, blade-row losses, and stage test losses. Coefficients are selected to match the known design-point performance, and the internal model provides the off-design performance. Coolant flow addition is allowed.

The AXOD code can also do a design calculation, but there is no built-in design-point loss model. As with the off-design calculation, the efficiency at the design point must be known so that appropriate loss coefficients can be selected. Also, stage work is specified by rotor inlet and exit tangential momentums, which are not convenient because their relationship to the more familiar values of blading angles and reaction is not readily apparent.

AXOD input includes the blade-row inlet and exit hub and tip radii and blading angles to define the turbine geometry. For each speed, first-stator total-to-static pressure ratio is varied between specified limits at specified increments to compute points along the speed line. The maximum allowable overall pressure ratio is that at limit load, defined as an axial Mach number of unity at the turbine exit. The output, available at three levels of detail, includes total and static efficiencies and pressure ratios, both overall and stage actual and corrected performance parameters, and flow velocities and angles at all calculation locations. A map file in NEPP format (ref. 17) can be obtained. The AXOD code is very robust and code failure usually indicates an input problem.

In an associated effort, turbine off-design prediction capability for cycle codes was enhanced. Maps generated by the PART code (ref. 26), which is often used to generate turbine maps for the NEPP cycle code, do not predict the limit load points on the speed lines. A methodology for estimating limit loads for any turbine map (ref. 27) was developed and subsequently added (not by this author) to the NEPP cycle code.

Radial-Inflow

The design code RTD and the off-design code RTOD, which are based on similar (but not fully identical) flow and loss models, are described in this section.

Design Code.- RTD (refs. 28 and 29) executes a conceptual design for a single-stage radial-inflow turbine having optimum incidence entering the rotor. A meanline analysis is performed across the stator and into the rotor, where the radii are constant over the blade span; at the rotor exit, where there are significant radial gradients, a spanline analysis is used. In the case of the radial-inflow turbine, where the flow is assumed uniform across the rotor inlet, the spanline analysis does not introduce errors due to shifting of flow in and out of sectors. The analysis can account for stator-endwall clearance flow that would occur with pivoting stators and for swept rotor blades. Splitter blades are allowed. The loss model includes stator and rotor friction and trailing-edge losses, vaneless-space loss, disk-friction loss, and rotor-exit clearance loss.

RTD input design requirements are power, flow rate, and rotative speed. The design variables include stator-exit angle, rotor-blade inlet angle, rotor-exit tip and hub radius ratios, and rotor swirl distribution. The output presents the computed rotor-tip diameter, all blade-row inlet and exit dimensions, diagram velocities and angles, and total and static efficiencies. RTD can write an input file for the RTOD off-design code. This code runs very reliably to completion.

Off-Design Code.- RTOD (refs. 30 - 32) predicts the flow rate and efficiency of a single-stage radial-inflow turbine as functions of pressure ratio, speed, and stator setting. The rotor blades can be either radial or swept, and splitters can be included. As with RTD, the stator-inlet and -exit and rotor-inlet flows are modeled with a meanline analysis, while a sector analysis (i.e., spanline) is used at the rotor exit. Clearance flow is included when a pivoting stator is used to provide a variable area. The loss model includes stator viscous and trailing-edge losses; a vaneless-space loss; and rotor incidence, viscous, trailing-edge,

clearance, and disk-friction losses.

The RTOD input includes the flowpath dimensions and the blading angles. A complete input file can be written by the RTD design code. Performance is calculated for constant speed lines from low to high pressure ratio, with limit load as an upper limit. Output can be obtained at different levels of detail from overall performance only (pressure ratio, flow rate, total and static efficiencies, etc.) to absolute and relative state conditions, velocities, and flow angles at all calculation locations. A map file in NEPP format (ref. 17) can be obtained. This code also runs reliably to completion.

CONCLUDING REMARKS

This report has described 12 computer codes, two of which are still undeveloped with regard to an acceptable accuracy of calculated performance, that determine the design geometry and the design/off-design performance of compressors and turbines, both axial and radial. These codes, among other things, provide the capability to include compressor and turbine design/performance analyses as part of airbreathing propulsion system conceptual design studies.

These codes do not use CFD analyses. They perform axisymmetric analyses of the velocity diagrams fore and aft of the blade rows using meanline, spanline, or streamline techniques. Conservation of mass and energy along with empiricisms for the blade-row losses provide the basis for the computations. Code execution times are very fast, a matter of seconds on a UNIX workstation and minutes or less on a PC. Most of the codes run quite robustly to completion.

However, these codes are only tools for use by the analyst. As with any craft, it is the skill of the craftsman that largely determines the outcome. The codes generally cannot detect inappropriate input or differentiate between acceptable and unacceptable design/performance solutions. The codes will only tell us whether or not the mathematics yield a solution and what that solution is. The user must contribute some knowledge to the process of selecting a best, or even an acceptable, design. Even with the knowledge in hand, designer's choice, based on personal/organization experience, still plays a part in the eventual choice of design.

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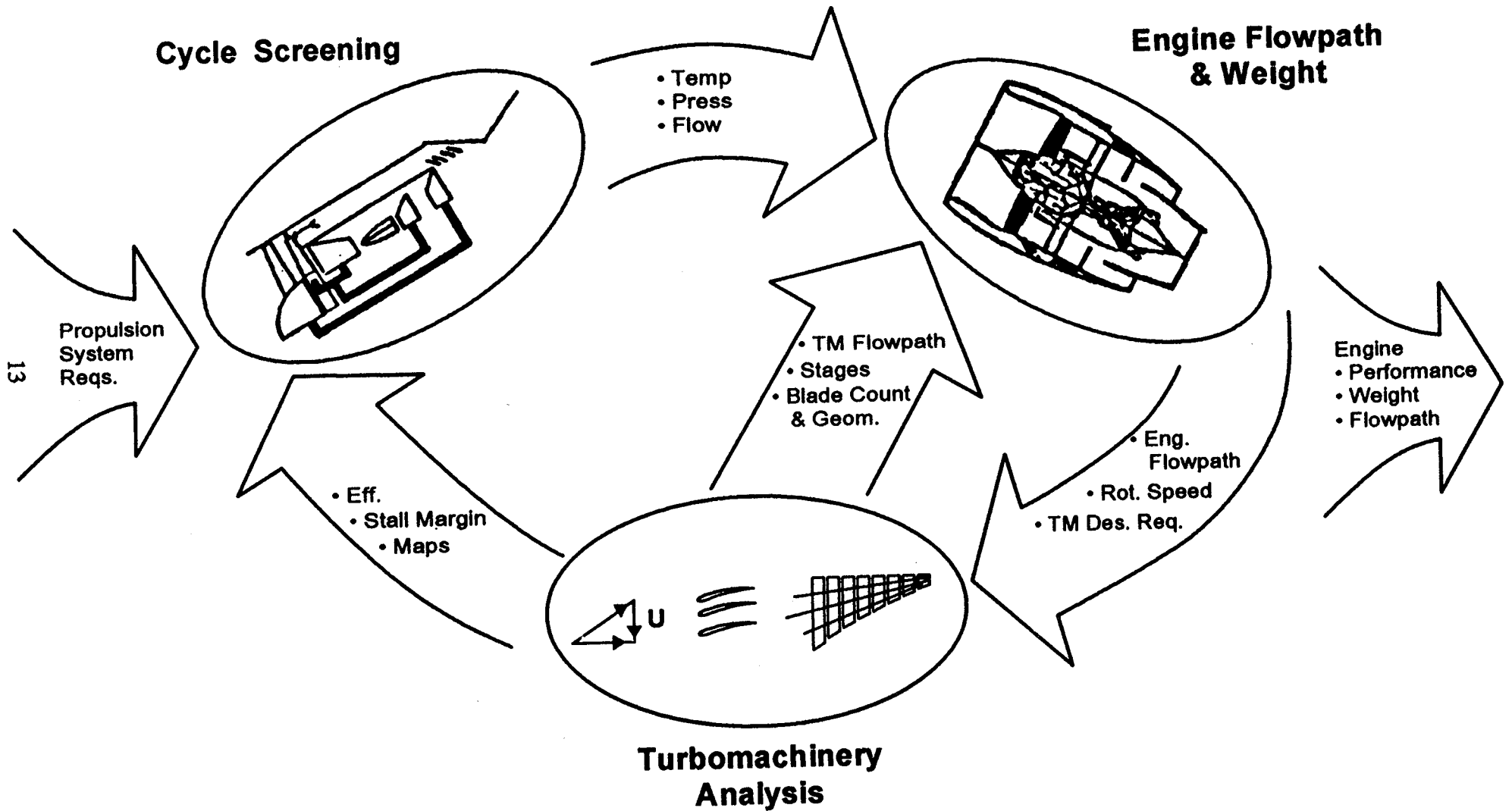
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Figure 1

Integration of Turbomachinery Analysis With Cycle and Flowpath



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