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Compressor Simulation: A Modular Approach

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INTRODUCTION

Today computers are virtually indispensable for compressor design and optimization studies. However, computer application to compressors are often extensions of historical approaches, automating and refining but not changing calculations that began with manual methods. They tend to fall into two basic categories. First is the anatomic approach which sums together individual analyses much like a performance ledger and is well suited for manual calculations. Second is a system approach where a complete system simulation produces both system and components losses. Often, the second approach is a computerized extension of the first, where individual calculations may be performed rapidly and permitted to recursively influence each other.

The advantage of the system approach is that the complicated interactions between the system and its components and between individual components can be analyzed. However, this approach normally requires excessive periods of time to develop and link the various analyses required for a given compressor in an executable form. As a result, the lumped parameter approach is most commonly used in system simulations, although some analysts develop simulations based on finite element or finite difference methods. Often, as a compromise, simulations based on finite element or finite difference methods are limited at most to only a few subsystems or components. A second disadvantage of finite element or finite difference methods is generally lower utility compared to the lumped parameter method. Any changes often require re-generating meshes or rewriting code.

The present method adopts the system approach. A modular strategy provides maximum flexibility without loss of thoroughness. Each individual module is a building block of the system which represents a compressor component, that can be separated from the system for independent analysis and development. Various modules may thus be modeled at any level of detail from lumped parameter to detailed finite element. The modules then link together through pre-determined parameters, or “connections,” which are defined to suit a particular module class or category. A graphic interface provides an intuitive, user-friendly environment. However, a wide range of model detail, from simplistic to extremely complex, is available for different levels of objectives and users.

BACKGROUND

At least as far back as the 1950s, published research activities were attempting to understand the performance of a compressor taking into account many factors, such as energy losses, mass flow losses, and volumetric efficiency (Thomsen, 1952, Shaffer, 1976, Horvay, 1978, Pandeya, 1978, Kleinert, 1986, Kato et al, 1996). The exergy method (Xu, 1992, McGovern et al, 1995, 1996), analyzes compressor efficiency based on the second law of thermodynamics.

A real compression process is never isentropic, due to leakage, heat transfer, and other losses. To have a simple representation of the compressor as a component in a more complicated system, such as air-conditioning or refrigeration systems, a constant polytropic exponent is often used. The dilemma of using this approach in
estimating compressor performance is that this constant can only be accurately determined after a detailed simulation or experiments, while we really need its value before such activity.

Given the power of computers, the system approach becomes more attractive to compressor design. The advantages of this approach are that it is possible to synthesize the compressor as a system, in which the complicated interactions between the system and its components and between individual components can be analyzed.

Chrustalev et al. (1996) developed a multistage model based on their more than 30 years experience, which had a block structure and from which each stage could be derived by excluding some elements. This approach seemed to be flexible, but the authors did not give details of the model. They mentioned that the inter-stage communications were quite complicated and the convergence of the method was slow.

Even with the computational power available today, the lumped parameter approach is still commonly used in system simulations. Computers automate the same calculation strategy used in the past. While some researchers or engineers are developing simulations based on finite element or finite difference methods (Morel, 1988, and Keribar 1988), simulations based on finite element methods are still computationally too expensive for a complete compressor system, much less for a whole refrigeration system (de los Santos, 1991). The existing finite element and finite difference packages also do not communicate well with one another which prevents an effective dynamic link among them. As a compromise some simulations based on this methods are limited to a subsystem, a part of complete compressor, or several components, or even a single component (Perez-Segarra et al. 1994, and Serra et al. 1996). Another disadvantage of finite element or finite difference methods is lower flexibility, compared to the lumped parameter method. Any change in the system requires re-generating meshes and recompiling code along with the associated debugging.

**Comparison of different approaches**

The anatomic approach, quite often, first assumes a polytropic coefficient and then calculates capacity, base efficiency, and thermodynamic properties such as pressure and enthalpy. Other losses, such as leakage, mechanical losses, and heat transfer are calculated with an implicit assumption that they do not affect the thermodynamic properties and are deducted from base capacity and efficiency. The advantage of this approach is its simplicity. It can be carried out step by step manually, without any need for iterations that solve simultaneous algebraic or differential equations. However, it has difficulty capturing interactions among different loss mechanisms. For example, the leakage alters the total mass in the compression chamber which in turn affects thermodynamic properties. The greatest shortcoming of the anatomic approach in accuracy often comes in extrapolating such models to extreme operating conditions without empirical recalibration.

The system approach takes the interaction among the parts of a compressor into account. For example, the leakage depends on the pressure of the compression chamber and, at the same time, the leakage affects the pressure of the compression chamber. Therefore, the determination of leakage mass flow is coupled with the calculation of compression chamber pressure. For another example, the torque produced from compression work affects the electric motor speed or even stalls the motor, while the variation of motor speed changes the duration of compression, suction, and discharge process. The penalty of this approach is that it is intrinsically more complicated than the anatomic approach. Simultaneous differential equations must be formulated and solved. But with the computational power of computers, even in PC's, this is no longer a barrier. However, inflexibility may be inherited in a complicated compressor simulation program. The prohibitive computational overhead of the past becomes prohibitive overhead in formulation, coding, and debugging. Increased speed and accuracy is paid for with reduced clarity and accessibility.

Finite element methods have become common, however, they are often restricted to analyzing components or subsystems. In this manner, they often augment the anatomic approach, giving greater resolution on the behavior of some of the individual elements, such as fluid flow or mechanics. The interaction among those aspects is typically limited to boundary values from the base calculations. Even when the base calculation has been automated, coding it to interact with finite element codes is difficult at best.
MODULAR MODEL

The present method takes a modular approach, specifically for the PC environment, in order to have maximum flexibility without loss of thoroughness in the simulation. A modular model has two primary subsets of components. The *modules* themselves represent actual compressor components or systems. The *connections* define how modules fit together and interact.

**Module concept**

The module, a building block of the system and a representation of a component in a compressor, is separated from the system for independent analysis and coding. Individual modules can be modeled in any level of detail, from lumped parameter to a detailed finite element level. The modules link together through pre-determined parameters requiring a module to accept and generate certain inputs and outputs. Given sufficient flexibility in the connection, interaction between a finite difference or finite element model is possible. Through a graphic interface, a compressor model may be developed from a library of modules without need for extensive coding or debugging. Individual refinement from in-depth analysis and formulation of various modules can take place offline and can be focused specifically on the issue at hand without regard to managing it’s integration in the greater model.

In a modular model, a set of equations, including differential and algebraic, are divided into subsets. Those subsets are the so-called modules of the model. For example, the differential equation representing the motor that calculate the motor magnetic torque, can be lumped together as a motor module. It takes the applied torque as input and calculates the motor speed and power consumption as output. Once this is running, a more advanced module that considers, for example, voltage and torque variation and temperature may be developed offline. In general, modules can be regarded as subroutines or data files in a complete computer program. Division of the system into subsets can be arbitrary, but a module generally has three characteristics.

First, it represents either a particular part, a mechanism, or an aspect of the compressor. Bearing modules represent the physical parts of bearings. The compression chamber represents more a process than a physical part, because it depends on interactions with other modules to define volume, pressure, mass, heat transfer, etc. The *geometry module* represents the kinematics of a particular compressor design, generating information about chamber geometry, port states, load s and load transfer, etc.

Second, a module should be as independent as possible. It can run with minimum specified inputs and is truly a subprogram or “minimodel” that is dedicated to modeling a particular aspect.

Third, it can be reconfigured through data input to adapt to any specific model. For example, the same bearing module can be used in reciprocating, rotary, scroll, or any other compressor type simply by specifying individual geometry. To maintain flexibility and clarity for the users, the classification of subsets needs special attention. The present approach divides modules into several types and standardizes the connections among those modules.

A simple model can be started with a only a few modules and gradually expanded and refined by adding more modules. Different levels of complexity would satisfy different needs of analysis. For instance, a basic model to study valve action may not require a motor or bearings so that those modules may be excluded. A refinement to study detailefluid flow losses may then add flow passage modules between the suction line and suction valve. This can all be accomplished with a minimum number of modules for the rest of the system or by working with an existing model without modification of the rest of the model except in areas of interest.

Several modules that accomplish a certain function can be further grouped together into a super-module. A basic example is a *compressor main body*, a super-module that consists of the geometry, chamber, port, valve, bearing, and other modules that make up a fundamental compression device, such as the mechanism of a single cylinder of a reciprocating compressor. This allows more complicated assemblies, such as multicylinder compressors, to be constructed without generating each cylinder separately. Thus users at different levels of understanding or with different design expertise can work with same set of modules. An expert in bearings can work on the bearing modules without looking into the details of the compression main body super-module, while a
compressor designer can go into the compression main body super-module to investigate the effects of each individual design parameter on the efficiency and capacity of the whole system.

Figure 1 Modules of a compressor model

Module types

A complete compressor model generally has a structure similar to that as shown in Figure 1. The modules can be divided into five types: fluid flow, mechanical, electromechanical, compression chamber, and geometry. The compressor main body is a super module, in which generic modules are assembled together in a specific way so that a specific type of compression process, such as reciprocating, rotary, scroll, screw or other, is represented. It contains the information of geometry configuration, compression process (compression chamber), flow and leakage paths, and the load characteristics specific for a particular type of compressor.

The fluid flow modules include valves, flow passages (channels or pipes), and suction and discharge ports and lines. The suction and discharge line can be defined as a constant pressure and temperature or specified as a function of time. In Figure 1, the suction gas from the gas sources goes to the suction valve through several flow passages, and then is fed into the compression chamber in the compressor main body module. The discharge gas coming out of the compression chamber passes through the discharge valve and goes to the other gas source though a gas passage.

The mechanical modules include a shaft and bearings. The shaft module takes the mechanical load and torque information from the compressor main body and distributes the load to the associated bearings and to the motor. The torque balance between motor and the sum of compressor and bearing loads occurs in the shaft module and determines the shaft angular velocity and angular position.

The motor module is an electromechanical module. It converts electrical energy into mechanical work and at the same time generates heat which is rejected into the fluid. The motor and other electronic control
mechanisms can be combined into another super-module where connections with fluid passages or other modules provide pressure and temperature input to the controls.

The compression chamber module converts mechanical energy from the motor into internal energy of the fluid. Therefore, it has both mechanical connections and fluid flow connections as well as heat transfer connections. However, the compression chamber module also needs information about its geometry and behavior depending on the compressor type being simulated. This information is provided by the geometry module, which contains information about the basic compression mechanism geometry and performs the calculations regarding compression chamber behavior, and load generation. These include the traditional kinematic calculations regarding the compression mechanism as well as information on fixed port openings and closings.

**Standard connections**

Standard connections are like sockets and plugs so that modules can be connected by "plugging in" to another module with the same type of connection. Standardized connections offer several advantages. First, the modules of the same type can be easily connected without assigning separate data exchanges. Second, modules of the same type can be easily exchanged. For example, a bearing module with a different degree of complexity or detail can be exchanged for another in a model as the focus of the analysis changes. Third, an attempt to connect incompatible modules, such as a mechanical connection between a bearing and gas passage would be rejected by the model. Finally, standard connections make it possible for a user without deep understanding of the underlying computer code to build or modify a model.

**Connection types**

Major categories of connections are fluid flow, mechanical, electrical, geometry, and heat transfer. A basic fluid flow connection includes mass flow rate, vapor quality, and two thermodynamic parameters that determine the thermodynamic state of the fluid. Mechanical connections can be further divided into two subcategories of linear motion and rotating motion. The former includes acceleration, velocity, position, force, and position of the force. The latter includes angular acceleration, angular velocity, angle, force, position of the force, and torque. Heat transfer connections include heat transfer coefficient, heat transfer area, temperature, and heat transfer rate.

While the connection type is related to its module type, a module can have more than one type of connection. The suction and discharge ports have fluid flow connections but might also have geometry connections in fixed port machines such as scroll or screw compressors. Bearings have mechanical connections, but can also have thermal connections to account for heat generation and rejection.

**CONCLUSIONS**

Adoption of modular techniques takes advantage of the best features of all modeling approaches. Module development, as in the anatomic approach, can focus on the behavior and analysis of individual subsystems without regard to their interaction with the rest of the compressor. However, the model, once constructed of linked modules, takes full advantage of interaction analysis as provided by the system approach. In addition, the prepackaged nature of the modules and preconfigured nature of the connections draws effort away from repetitive individual analysis of components and redirects the focus to details of the compressor design and interaction, which is after all the ultimate interest of the compressor designer.
REFERENCES


