A method for the geometrical analysis of twin-shaft rotary displacement machines

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Abstract

The thermodynamic simulation of screw machines on the basis of a chamber model requires, dependent on the complexity of the physical models, adapting the geometry of displacement machines with reference to rotation angle values such as the working chamber volumes [1]. A general calculation of the geometrical values required is possible if the machine geometry is also being subjected to a valid analysis, and essential elements specifically required for a chamber model have been identified and logically interconnected. In order to make this complex process fully automatic, a method for analysing displacement machines on the basis of an abstract surface representation has been developed and implemented. The logical identification of the working chambers and gap connections is used as the basis for the geometrical calculations. Employing this method in the program language C++, according to the paradigms of object-orientated programming, guarantees good serviceability and high potential for further development.

1. Introduction

Simulation is an accepted approach to the theoretical examination of technical systems on the basis of a model which can combine any selection of physical influences. The advantage of a simulation is that it offers, for example, the option of analysing systems which do not actually exist at present, or carrying out experiments which would be extremely complex in practical terms. Simulation can contribute to a better understanding of technical systems, and also reduce costs within the framework of product development. A vital requirement for the efficient deployment of simulations in the development of fluid energy machines is the availability of a suitable software package, consisting of PreProcessor, Solver and PostProcessor. Only when the software package successfully integrates these three phases can the simulation be smoothly integrated into the value creation chain of the product.

For the simulation of displacement machines and in particular of vacuum pumps, there exist at the present state of the art primarily four different forms of modelling. These range from simple functional correlations between inlet and outlet values to modelling multi-phase flows by means of numerical flow simulation and grids which can be moved and deformed.

a. Modelling on the basis of simple functional correlations
b. Modelling on the basis of a chamber model
c. Modelling on the basis of a characteristics procedure
d. Modelling on the basis of a numerical flow simulation

Modelling on the basis of functional correlations may be capable of showing qualitative connections between basic performance values (e.g. volumetric efficiency), of the operational parameters, but it is generally not possible to quantify the results because factors such as gap flow, heat transfer, and dissipative processes during the charge transfer are not taken into account. For the quantitative examination of displacement machines, the modelling depth of this method is inadequate. As modelling becomes more complex, leading eventually to simulation on the basis of numerical flow simulation, the degree of detail of the results which can be achieved increases, but so does the amount of work required for model formation, verification and validation. Modelling on the basis of a chamber model is based on the assumption that the working chamber of a displacement machine can be represented in terms of a number of volumes, the fluid content of which is in a homogeneous state, and condition values for the fluid are simply functions of time and rotation angle. The distinguishing feature of the chamber model method is the balancing of energy and mass between the working chambers in order to calculate the quasi-constant changes of state. With the help of the one-dimensional characteristics procedure, which, in addition to mass and energy conservation in a differentiated form, contributes conservation of momentum, non-constant phenomena of the displacement machine, such as charge change, can be represented. A prerequisite for this is that the acoustically relevant geometry of the screw machine is correctly captured, and that the relevant non-constant effects can be approximated by even waves. Considering the entire range of modelling options with sufficient depth from b) to d), only numerical flow simulation offers straightforward, intuitive software solutions which support the user, in particular during model generation and the evaluation of results, so that deploying this kind of simulation can be considered as worthwhile.

However, numerical flow simulation is only of limited use in connection with displacement machines, because the complex rotor geometry and the significantly varying time-dependent geometrical measurements in working chambers and gaps make the generation of high quality calculation grids virtually impossible [2][3]. In addition, the choice of turbulence model also has a significant effect on the representational quality of the flow simulation and the degree of accuracy which can be achieved. But turbulence models which are capable of representing the three-dimensional non-constant flow in displacement machines are not available [4]. For these reasons, the best current solution is to reduce the modelling complexity to the requirements of a chamber model or a characteristics procedure. A computation for displacement machines on the basis of a chamber model is available via the *KaSim* software, which has already been verified for a large number of applications. A disadvantage of *KaSim* is the lack of a PreProcessor, which would support users during the geometrical abstraction phase, and in the choice of physical models. Theoretically a number of 2D and 3D CAD programs are available for the user, but the manual choice and calculation of all the necessary geometrical values is very time-consuming. For this reason, the development of specific analytical software for the automatic generation of a chamber model which can be used in the productive deployment of *KaSim* is essential.

2. Requirements of a method for automated geometrical analysis

The development of a universally valid method must begin with a catalogue of requirements. This catalogue is based partly on the personal experience of the developer, and partly on requirements and wishes of the industrial partners. These requirements can be sorted into two sets of categories, one for machine geometry, and the other for applicability of the method.

2.1 Machine geometry

The chamber model generator to be evolved should be as generally applicable as possible. For this reason, any twin-shafted rotary displacement machine whose rotor profiles can be described by means of a defined number of points is acceptable. A variation in rotor profile along the rotation axle should be permissible. This modification can be either a function for the rotor gradient or a truly varying profile as in the case of conical rotors. This requirement also applies for the geometry of the casing. Here it assumed that there is no need to analyse the entire casing. For the generation of a chamber model it is only necessary to consider the internal boundary surfaces. The inlets and outlets of the screw machine are treated separately. They should not be restricted in either number or position, but should be permitted in any possible combination, as long as they can be classified as either radial or axial.

The geometrical data required for the individual components must be provided by the user, with, in principle, both two- and three-dimensional input formats being provided for. Exceptions in this connection are the inlet and outlet areas, which must always be supplied in three-dimensional form.

2.2 Applicability

The application requirements of the method to be developed can be summed up in terms of simple and intuitive operation. With regard to seamless integration of the method into the working process, and consequent time and effort saved for the user, this point is a vital feature of a PreProcessor compared with manual modelling. This would include, for example, the option of having the necessary parameters calculated automatically by means of adaptive algorithms, or at least the capacity to make reasonable suggestions. In addition, user interaction should be reduced to a minimum. A direct interface with *KaSim*, which would support all the physical models of the thermodynamic simulation program, would radically reduce the amount of additional work required in the post-processing of the geometrical data.

3. The development of a method for automatised geometrical analysis

The universally valid geometrical analysis of displacement machines tends to be a very complex process, requiring a three-dimensional, rotation angle dependent analysis of the geometry under examination. One possible solution is the choice of a deductive top-down method. Here, the initially unknown problem of the geometrical analysis is split up into a number of sub-steps. As the objectives gradually become clearer, the aims are both to achieve usable and/or known part-solutions, and also to simplify later implementation.

3.1 Structure of the PreProcessor

The complete geometrical analysis is extracted from the composite block of necessary data and program interfaces, and reduced to the rotation angle dependent identification of the working chambers and connections (**Figure 1**). This process makes possible a further specialisation of the method to be developed with reference to its central task, which is the logical-geometrical analysis of the geometry in question. The identification of the working chambers can, as before, be reduced to a series of analyses of single rotor positions, in which case, as a next step, the working chambers at every position of the rotors would have to be combined with one another by means of suitable criteria. There is no point in carrying out an identification of the connections unless the working chambers have been identified.

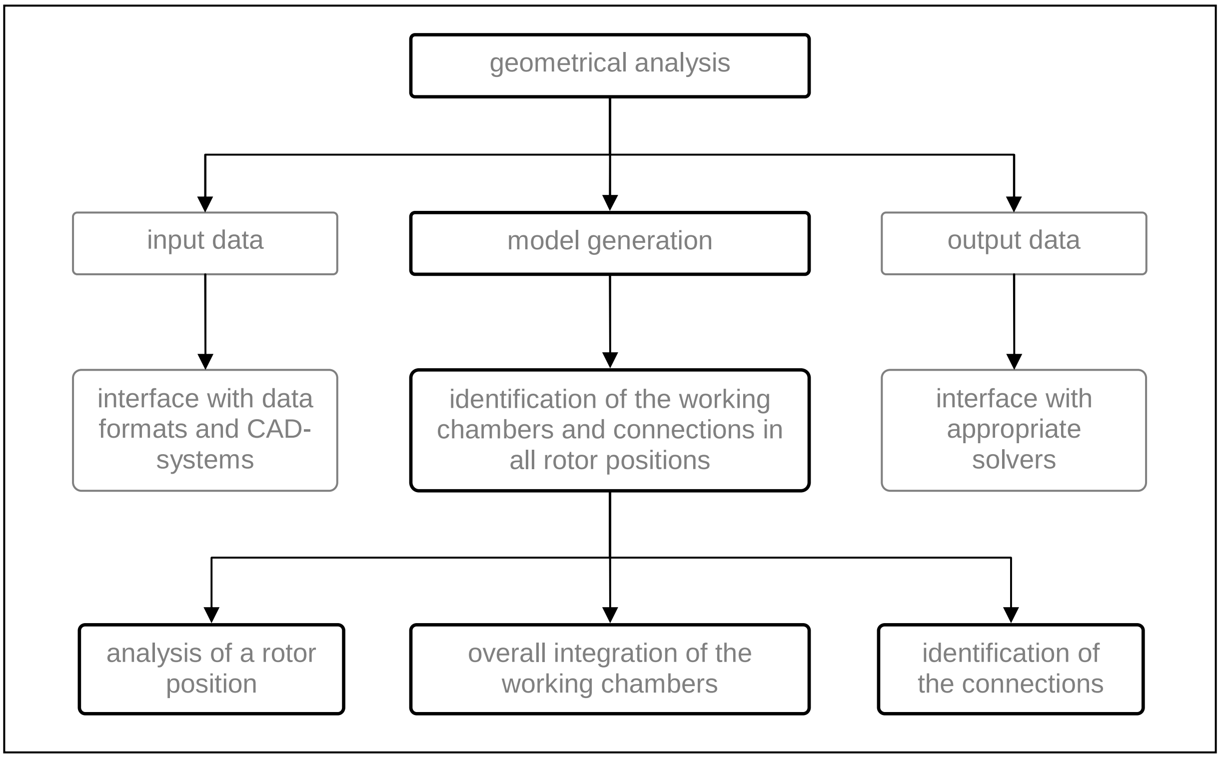

Figure 1: Schematic top-down-representation of the structure of the PreProcessor and classification of the rotation angle dependent identification of the working chambers and connections

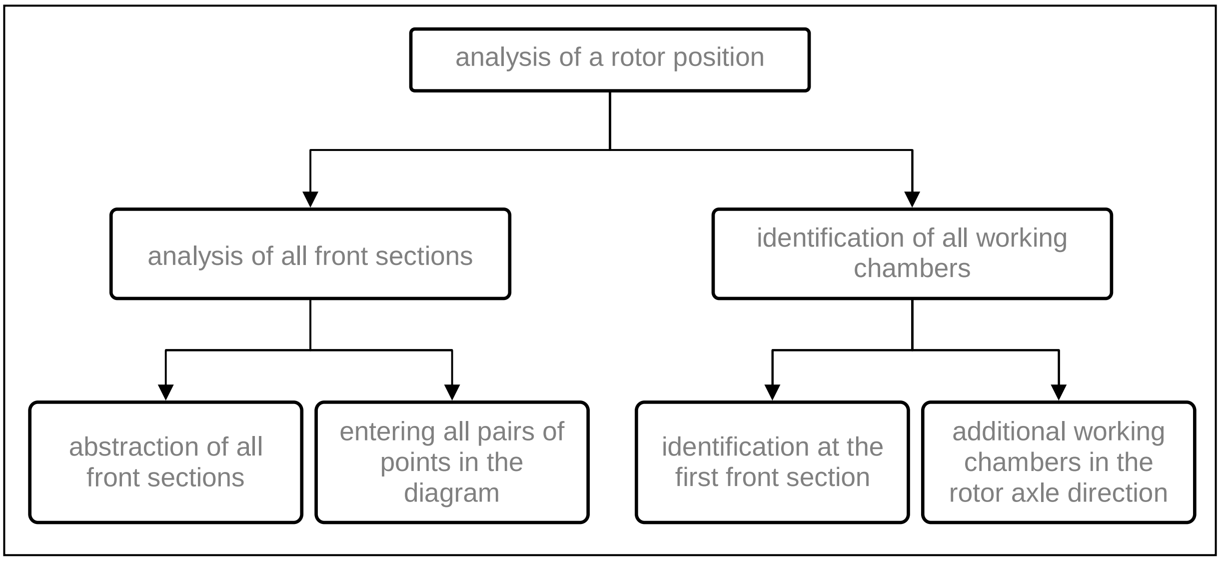

Figure 2: Logical-geometrical analysis of a rotor position

For this reason the process of analysing the rotor position will be dealt with in detail in the following. The aim of this part of the task, the analysis of the rotor position in order to identify the working chambers, is to replace a component-based approach for the input data (rotor, casing, etc.) with a working chamber-based approach, without changing the actual geometrical data. This procedure guarantees a high degree of flexibility for the implementation process, in connection with the representation of the component geometry where there is an element of choice for the user. **Figure 2** shows the principal sub-steps of the rotor position analysis, with step by step consolidation. The most important step in this process is the separation between the geometrical analysis of the front section and the identification of the working chambers. The implementation of these two tasks is clarified below.

3.2 Component-related front section analysis

A reduction in geometrical complexity is achieved by means of the ingenious deployment of a so-called ‘sweep’ method. With the help of a step by step examination of the machine geometry, a three-dimensional analysis is reduced to a two-dimensional view for the relevant front section. The great advantages of this procedure are the simplification of all geometrical calculations and the limitation of working chamber identification to the front section. At the front section, the working chamber appears as an area surrounded by a closed curve (**Figure 3**).

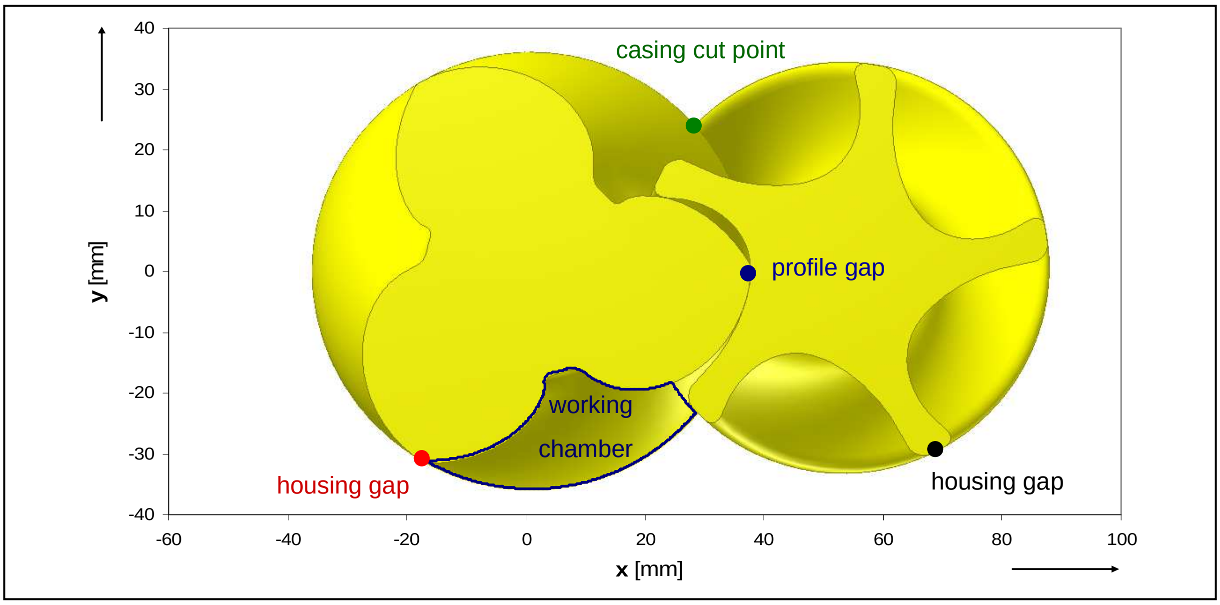

Figure 3: Exemplification of characteristic points and a working chamber at the front section

A principal disadvantage here is the discontinuous representation of the actual machine geometry by means of a random number of disconnected front sections. The identification of the working chambers is made more difficult both because a new identification of the working chambers has to be carried out for each front section, and because these must be interconnected via suitable criteria. As the later interconnection of two front sections is likely to involve very complex calculations, this intrinsic disadvantage of the ‘Sweep’ method is compensated for by a specifically adapted, highly abstracted representation of the component geometry. This representation, also referred to in the following as a diagram, exploits a significant advantage of the front section analysis: the front section of a machine geometry consists of a large number of components, along with their curves and precise geometrical data, but it can in principle be characterised with a small number of point-pairs. The characteristic selected pairs essentially describe the gap bordering the working chamber, which is defined as the typical minimal clearance between two components at the front section (Fig. 3). As any gap height is permitted, a gap will always be described via two points, one for each component.

A diagram refers here to a two-parameter surface, which is formed by ‘unwinding’ along the circumference (**Figure 4**). Parameter ‘s’ on the circumference corresponds to the curve length of, for example, the rotor profile at the front section. Parameter ‘z’ represents the position of the front section being examined in rotor axle direction. The characteristic point pairs, which represent the abstracted front section resulting from the analysis, are inserted into the diagram for the component in question, with two pairs of points in s-direction always forming an abstract section, called segment.

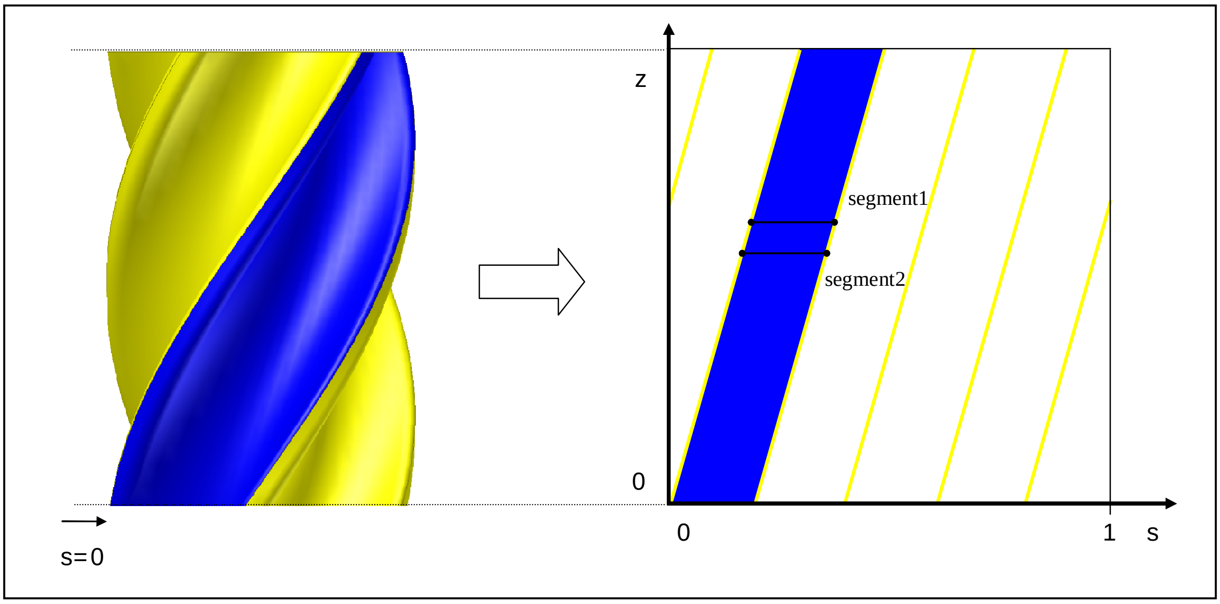

Figure 4: Diagram exemplifying an ‘unwound’ component surface

The characteristic point pairs perform several tasks within the framework of the diagrams. First, they contain the necessary geometrical information for the later identification and calculation of the gap connection. In addition, every point-pair is an element in two diagrams, (e.g. rotor and casing), so that an interconnection occurs between the diagrams, and also between the abstract segments of different components. This interconnection can be used for the identification of the working chambers in the front section, as it takes place logically, and quite independently of the actual machine geometry. The second advantage of diagrammatic representation lies in the rule-based interconnection between the segments in two adjacent sections. If two segments in successive front sections belong to the same working chamber, these segments will be interconnected (**Figure 5**).

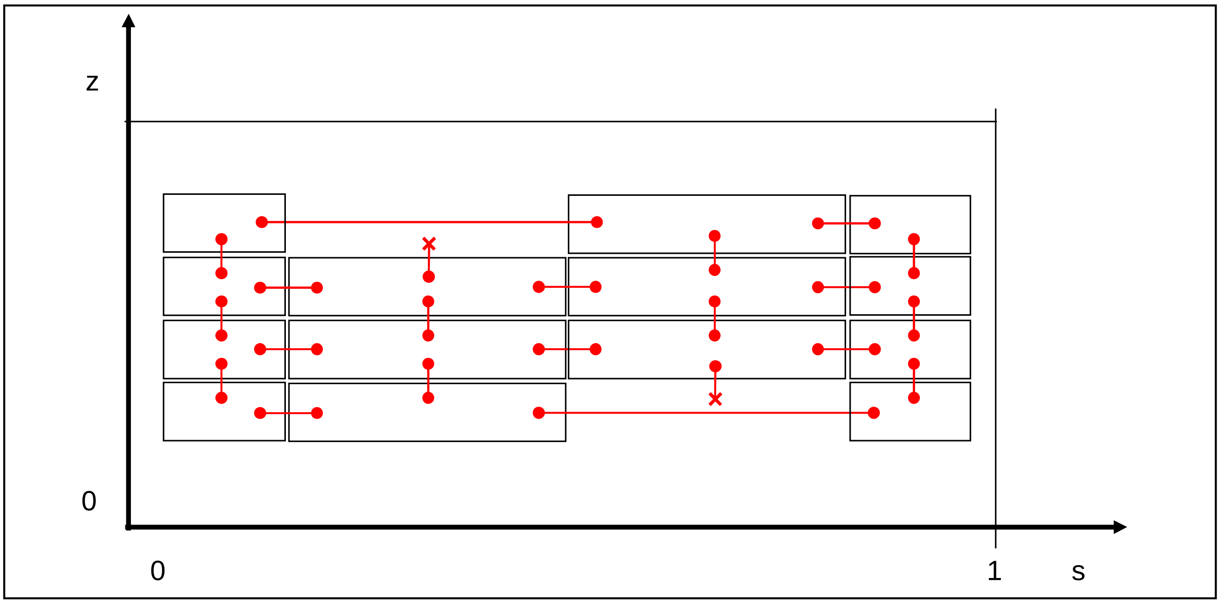

Figure 5: Interconnection of abstract segments in a diagram

In general, a segment has two connections, in each of the two parameter directions. The connection in the ‘s’ direction permits a working-chamber orientated examination of the selected front section, while the connection in the ‘z’ direction focuses on an examination of the component surfaces belonging to the working chamber. Once the connections have been set, this has the advantage of reducing calculation times when the diagrams are evaluated later. This would be done in order to identify the working chambers or to calculate geometrical values, as ‘tracking’ the connecting paths itself is no longer linked with any geometrical calculations. Interconnecting the segments occurs automatically as they are integrated into the diagram. At this point, along rule-based lines, the geometrical position of the characteristic points in the front section will be used to decide which segments in the ‘z’ direction must be interconnected. Instead of a mathematically complex computation of the overlap between two areas enclosed by two non-convex polygons, it is only necessary to calculate and compare the three-dimensional distances between the central points of the connecting line of characteristic points. By this means, all relevant changes in the front section geometry relating to working chamber distribution can be covered, and transferred to the abstract diagrammatic representation by entering the interconnections.

3.3 Identification of the working chambers at a particular rotor position

Initially, the identification of the working chambers is limited to the front section, using not the real geometry, but the abstracted front section in the diagrams. The main procedure is illustrated in **Figure 6**. The abstract segments of all diagrams of any selected front section are stored in a list, and a random element from the list is chosen as the starting segment. Next, a suitable adjoining segment is located. As a result of interconnection between the segments by means of the characteristic point-pairs, three possible candidates per segment boundary are always available.

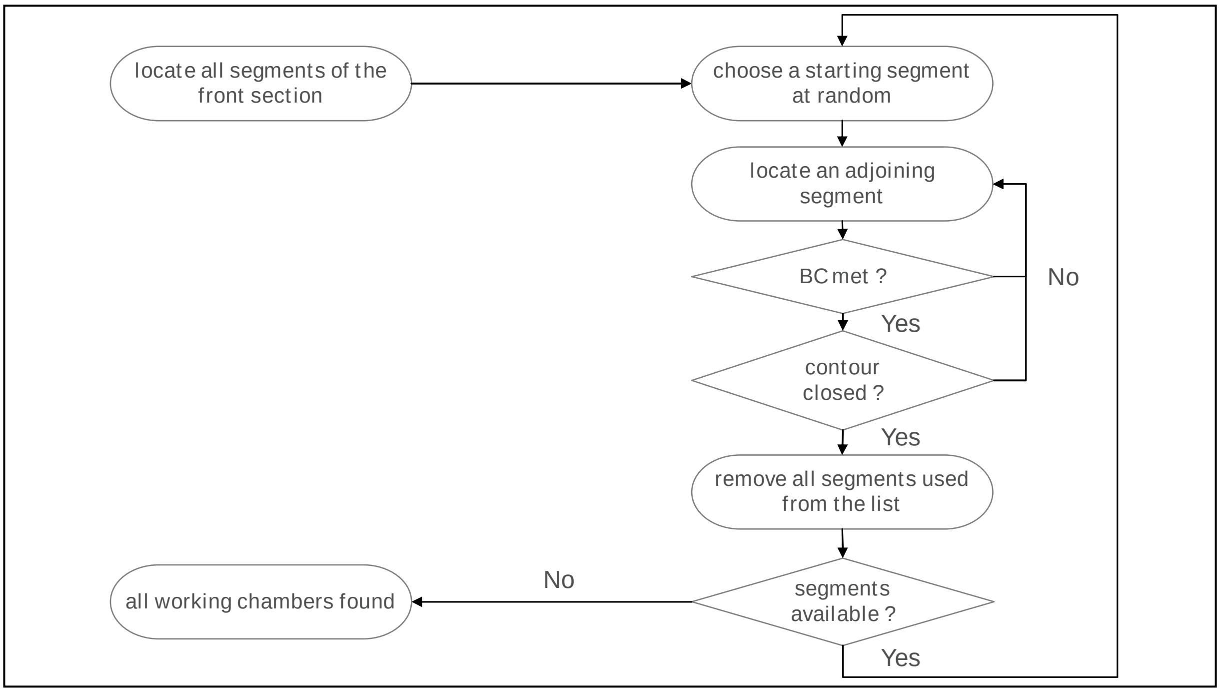

Figure 6: Procedure for identifying the working chambers at the front section

The search for the right segment in terms of identifying the working chambers can be carried out by means of various mathematical approaches, but here a very pragmatic, recursively constructed method is introduced. This method judges a recursion string to be admissible, on the basis of the preset boundary conditions (BC), if it fulfils all the conditions. The boundary conditions consist mainly of the preset requirements for the maximum number of segment figures per component and working chamber. The search for an adjoining segment ends as soon as the contour of the working chamber at the front section closes. All segments used for this working chamber are then removed from the list created at the start, and a new starting segment is selected. When all segments have been assigned to working chambers, the algorithm is completed.

The identification of the working chambers takes place initially in the first available front section of the diagrams. If this consists of an ‘unwound’ rotor geometry, all working chambers are already identified. In order to cater for new working chambers formed along the rotor axis in the case of a ‘wound’ rotor geometry, discontinuity in the interconnections is exploited. Segments in the ‘z’ direction which have no predecessor (Figure 5) are very likely to belong to a new working chamber. This means that working chamber identification need not be applied in every front section, but only repeated in those front sections which have no predecessors in their segments. If a chamber in a front section of this kind consists entirely of segments without a predecessor, we are dealing with a new working chamber.

3.4 Integration of the working chambers in all rotor positions

The analysis of an individual rotor position is repeated for the whole rotation angle area under examination, and it supplies the working chamber allocation in all rotor positions. A further analysis of the total geometry with reference to the connections between the working chambers and other factors (e.g. inlet and outlet), requires an interconnection of the working chambers in all rotor positions. A reasonable approach is assignment based on the centroids of the working chamber volume. Two adjacent rotor positions are continually compared, with a view to entering the distances between centroids of two chambers into a matrix. With the help of optimisation procedures, setting maximum distances, and under the boundary condition that male and female working chambers must not be interconnected, the matrix can be so effectively cleared of unwanted data that only unambiguous correlations between two rotor positions remain. This also includes working chambers with no predecessors or successors. As a result of the integration of the working chambers in all rotor positions, all working chambers are available in three dimensions, dependent on the rotation angle, and in the geometry specified by the user. Consequently, an evaluation with reference to the interconnections can be directly represented in a three-dimensional and rotor angle dependent form, without it being necessary to assign the connections according to the angles of rotation.

4. Implementing the method for the analysis of double-shaft rotary displacement machines

The aim of implementation is the rigorous application of the method described. An important feature is that the separation between logical-geometrical analyses and geometrical calculations should also be maintained in the implementation phase. In addition, data interfaces which have so far not been taken into account can also be included with the help of a flexible data structure, so that, in particular for the input of the geometrical data, virtually any data format (e.g. DXF or IGES) can be supported. Implementation takes place here in the object-orientated programming language C++, using standard libraries exclusively, so that the program which is created is independent of the platform. It can be compiled under either Windows or Unix systems, and will run accordingly.

Independently of the implementation of the method itself, a graphic user interface is being developed, which is intended to help the user with the process of model generation. This interface will include, as an important feature, visualisation methods which can represent both the imported geometrical data and the calculated capacities and connections. The user also has the option of editing the model data generated without knowledge of the data formats in question.

5. Summary

The method presented within the framework of this article consists basically of a front section based geometrical analysis, and an abstract representation of the machine components by means of a two-parameter diagram structure, which makes it possible to produce a universally valid three-dimensional analysis of twin-shaft rotary displacement machines. The result of the analysis is a working chamber orientated presentation, also in three-dimensional form, of the geometry supplied by the user, which can serve as a basis for further geometrical calculations. The actual implementation of the method involves, up to the present, an analysis of the three-dimensional geometric model and of the geometric rotation angle dependent values of the capacities and connections for a chamber model simulation.

The data output is in a format which the thermodynamic simulation program *KaSim* can understand. For the future, further developments of both the method and the evaluation algorithms are planned. Possible starting points are an automatic coupling of the thermodynamic calculation to a mechanical simulation, with a view to producing a complete computation of the thermal situation and resulting heat deformation, or the creation of a one-dimensional model for a simulation on the basis of a characteristics procedure.

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[1] Janicki, M. *Modellierung und Simulation von Rotationsverdrängermaschinen*
Dissertation, Universität Dormtund, 2007

[2] Kauder, K; Stratmann, D *Numerische Strömungsuntersuchung der Gasspaltströmungen am Hauptrotor-Gehäusespalt in Schraubenmaschinen*
In: Schraubenmaschinen Nr. 10, S. 49-62, ISSN 0945-1870, Universität Dortmund, 2002

[3] Kovacevic, A.; Stosic, N.; Smith, I.K. *Analysis of screw compressor performances by means of three-dimensional numerical modelling*
International Conference on Compressors and their systems 2001
S.23-32, ISBN 18605833 X, Institute of Mechanical Engineers, 2001

[4] Sachs, R. *Experimentelle Untersuchungen van Gasströmungen in Schraubenmaschinen*
Dissertation, Universität Dortmund, 2002