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Structural analysis in control systems design of hydraulic drives☆

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Abstract

The design of hydraulic control systems is a complex and time-consuming task that, at the moment, cannot be automated completely. Nevertheless, important design subtasks like simulation or control concept selection can be efficiently supported by a computer. Prerequisite for a successful support is a well-founded analysis of a hydraulic system's structure. This paper provides a systematics for analyzing a hydraulic system at different structural levels and illustrates how structural information can be used within the design process. Another important point of this paper is the *automatic extraction* of structural information from a circuit diagram by means of graph-theoretical investigations.

Keywords: Algorithms and knowledge-based methods for CACSD; Structural analysis of hydraulic systems; Graph theory

1. Introduction

Hydrostatic drives provide advantageous dynamic properties and therefore represent a major driving concept for industrial applications. Large-scale hydraulic systems — such as plants in marine technology as well as drives for machine tools — possess a large number of actuators. Consequently, sophisticated interdependences between single components or entire subsystems may occur, which leads to a variety of challenging and demanding design and control tasks. As a representative example with respect to complexity and dimension, Fig. 1 shows the circuit diagram of a cold-rolling plant (Wessling, 1995; Ebertshäuser, 1994). Here, more than 20 actuators work on the coiled steel strips.

Designing such large hydraulic control systems implies a systematic procedure. In practice, this is done rather implicitly — based on the intuition and the experience of the human designer. This paper introduces a systematics of hydrostatic drives which reveal their underlying structures, as well as relations and dependencies among substructures. This approach allows a thorough structural analysis from which fundamental conclusions for the automation of the design process can be drawn.

The concepts of this paper have been realized and integrated within ^{art}*deco*, a knowledge-based system for hydraulic design support (Stein, 1995). Currently, ^{art}*deco* combines basic CAD facilities tailored to fluidics, checking and structure analysis algorithms, simulation methods, and basic design rule processing.

The operationalization of hydraulic design knowledge requires a formal definition and automatic extraction of structural information from a circuit diagram. The paper contributes within these respects; it is organized as follows. Section 2 describes both conceptually and exemplarily the structural levels at which a hydraulic system can be investigated. Section 3 briefly discusses the benefits that go along with a structural analysis. Section 4 precisely defines different types of couplings between the functional units of a hydraulic system, hence establishing a basis for a computer-based analysis. Moreover, it is outlined how a structural analysis is automated. Section 5 outlines the exploitation of structural information within ^{art}*deco*.

2. Structural analysis of hydraulic systems

The majority of hydraulic systems is designed by exploiting the experience and intuition of a single engineer. Due to the lack of a structural methodology,

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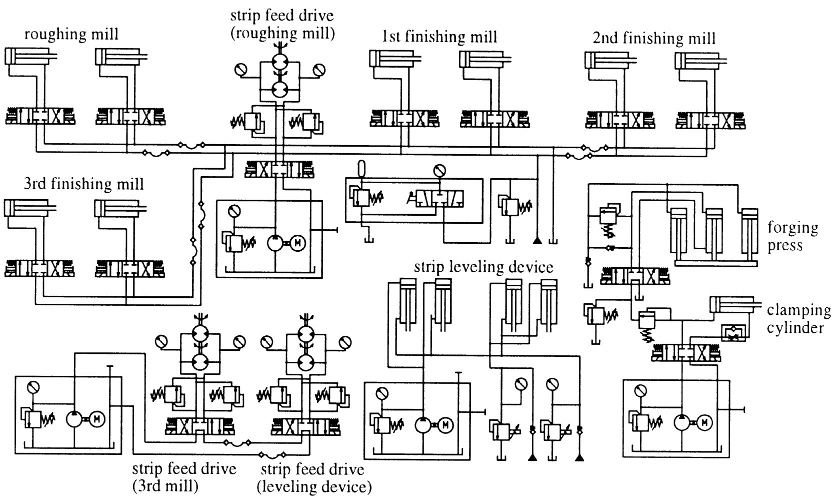

Fig. 1. Hydraulic circuit diagram of a cold-rolling plant.

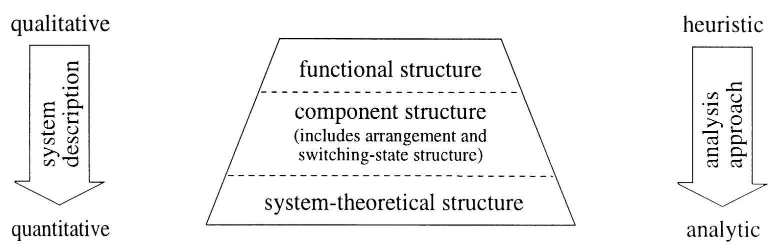

Fig. 2. Structural levels of hydraulic systems.

a thorough analysis of the system structure is not carried out. Instead, a limited repertory of possible solutions is used, making the result highly dependent on the capabilities of the individual. Such an approach is suitable only for recurring design tasks with little variation.

In the following, a systematics of the structural set-up of hydraulic plants is introduced which leads to a problem-oriented system analysis. Its application to a hydrostatic drive — given as a preliminary design — facilitates a consequent and purposive derivation of structural information, which is necessary to make the system's behavior meet the customer's demands.

2.1. Structural levels of hydraulic systems

The systematics developed here is based on three levels of abstraction (Vier et al., 1996). The differentiation between functional structure, component structure, and system-theoretical structure corresponds to system descriptions of different characteristics (Fig. 2). From this distinction results an overall view of how to influence the system's behavior.

To illustrate the concept of structural levels, we will concentrate on a sample subsystem of the cold-rolling plant, the four-roll stand is sketched in Fig. 3 (Ebertshäuser, 1994).

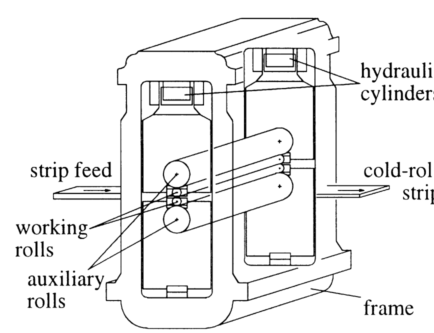

Fig. 3. Setup of a four-roll stand of the cold-rolling plant.

The *functional structure* shows the fundamental modes of action of a hydraulic circuit by analyzing the different tasks (functions) the plant has to fulfill. It represents some kind of qualitative system description. A key element within the functional structure is the so-called "hydraulic axis", which is defined as follows.

Definition 2.1 (*Hydraulic axis*). A hydraulic axis A represents and fulfills a subfunction f of an entire hydraulic plant. A defines the connections and the interplay among those working, control, and supply elements that realize f (Vier, 1996).

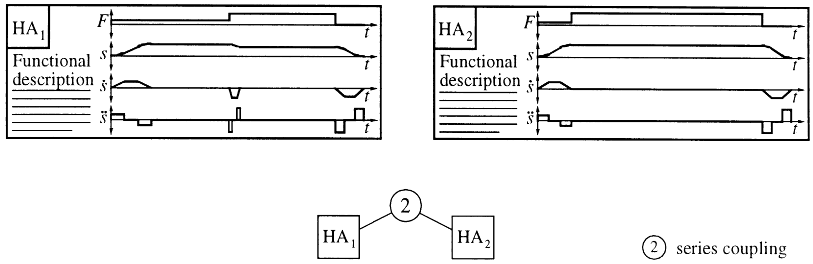

Fig. 4. The roll stand described at its functional level.

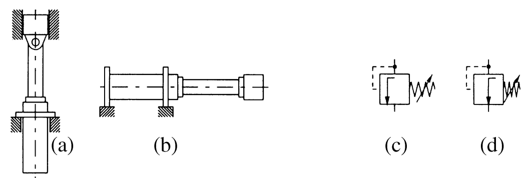

Fig. 5. Examples for arrangement structures (a, b) and switching-state structure (c, d).

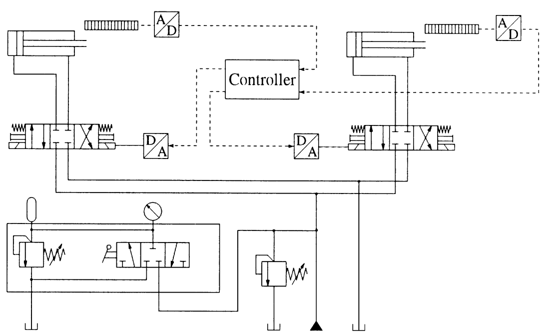

Fig. 6. Description of the roll stand at the component level.

The hydraulic actuators of the four-roll stand perform two tasks each of which defined by a directional load and motional quantities:

$$\text{function}_1 = \left[\boldsymbol{F}_1^{\mathrm{T}}, \boldsymbol{x}_1^{\mathrm{T}}, \dot{\boldsymbol{x}}_1^{\mathrm{T}}, \{\ddot{\boldsymbol{x}}_1^{\mathrm{T}}, \ldots\right]^{\mathrm{T}},$$

$$\text{function}_2 = \left[\boldsymbol{F}_2^{\mathrm{T}}, \boldsymbol{x}_2^{\mathrm{T}}, \dot{\boldsymbol{x}}_2^{\mathrm{T}}, \ddot{\boldsymbol{x}}_2^{\mathrm{T}}, \ldots\right]^{\mathrm{T}}.$$

A representation of the roll stand at the functional level is given in Fig. 4. The detection of hydraulic axes and their interdependences admits far-reaching conclusions, which are stated in Section 3.

On the level of the *component structure* the chosen realization of a function is investigated. The arrangement structure comprises information on the hydraulic elements (pumps, valves, cylinders, etc.) as well as their geometric and physical arrangement (Figs. 5a and b). By the switching-state structure the entirety of the possible combinations of switching positions is characterized: A valve, for instance, can be open or closed (Figs. 5c and d). Fig. 6 depicts the representation of the roll stand at the component level.

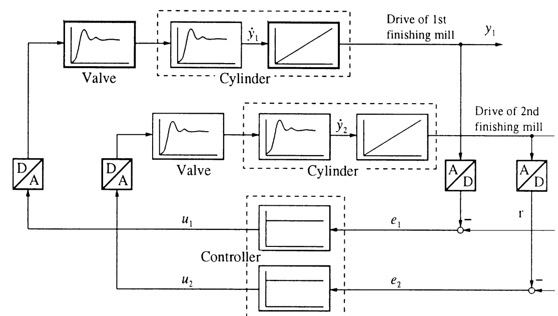

Fig. 7. Description of the roll stand at the system-theoretical level.

The *system-theoretical structure* contains information on the dynamic behavior of both the hydraulic drive as a whole and its single components. Common ways of describing dynamics are differential and difference equations or the state-space form (Schwarz, 1991)

$$\sum_N : \begin{array}{l} \dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), u(t)), \boldsymbol{x}_0 = \boldsymbol{x}(t_0) \forall t \geq t_0 \\ y(t) = h(\boldsymbol{x}(t), u(t)), \boldsymbol{x} \in \mathbf{R}^n; y, u \in \mathbf{R}. \end{array}$$

The system-theoretical view comprises information on the controlled quantities, as well as the dynamic behavior of the controlled system. The block diagram in Fig. 7 reveals the system-theoretical structure of the roll stand.

By comparing analysis and simulation results with the performance demands at the drive, a decision can be made for each hydraulic axis whether open- or closed-loop control concepts are adequate. In a further step, an appropriate control strategy (linear, nonlinear, etc.) can be assigned (Föllinger, 1992; Unbehauen, 1994).

Remarks. While the functional structure yields a qualitative representation, the system description becomes more quantitative at the component and system-theoretical level, respectively. Moreover, the analysis of the structural set-up shows in which way the behavior of a hydraulic plant can be influenced (cf. Fig. 2): (1) at first, the functional structure must be considered as invariant, because it results from the customer's demands. Only if the given structure proves to be unsatisfactory, a modification — resulting from a heuristic analysis approach — is advisable; (2) note that at the component level, a combination of heuristic and analytic methods is required for the variation or exchange of hydraulic elements, which form the controlled system; (3) the system-theoretical level facilitates the investigation of the dynamic behavior: control theory provides an analytic approach for the selection of a suitable control strategy, parameterization, etc.

2.2. Hydraulic axes and their couplings

Focusing on the investigation of the functional structure of hydraulic systems, the detection and evaluation of hydraulic axes is of central interest. Their analysis contributes to a deeper understanding of the inner correlations of the plant and provides an overview of the energy flows with respect to the functions to be fulfilled.

The definition of the hydraulic axis given in Section 2.1 is based on the criterion of elements working together in order to fulfill a single function. Note that several actuators (hydraulic motors/cylinders) may contribute to the same function, thus forming a single hydraulic axis (Fig. 8). This situation is given for

(a) identical sub-circuits that are controlled by one single control element,
(b) synchronized movements that are carried out by open or closed loop control, or
(c,d) mechanical couplings such as guides and gear units that enforce a unique behavior.

Beyond the consideration of isolated hydraulic axes, it is necessary to investigate their interdependences. The following coupling types have been worked out

Level 0 (*No coupling*.) Hydraulic axes possess no coupling, if there is neither a power nor an informational connection between them.

Level 1 (*Informational coupling*.) Hydraulic axes which are connected only by control connections are called informationally coupled.

Level 2 (*Parallel coupling*.) Hydraulic axes which possess their own access to a common power supply are coupled in parallel.

Level 3 (*Series coupling*.) A series coupling connects the hydraulic axes whose power supply (or disposal) is realized via the preceding or the following axis.

Level 4 (*Sequential coupling*.) A sequential coupling is given, if the performance of a following axis depends on the state variables, e.g. the pressure or the position of the preceding one in order to work in a sequence.

Applying the concept of functional structure to the cold-rolling plant of Fig. 1, 15 hydraulic axes along with their couplings can be found. The left-hand side of Fig. 9 envisions the membership of the components in the diagram to the axes, the right-hand side shows the entire coupling scheme in the form of a tree.

3. Benefits of a structural analysis

A structural analysis of hydraulic systems reveals basic design decisions. Especially the functional analysis, which is based on the detection of a system's hydraulic axes, will simplify the modification, the

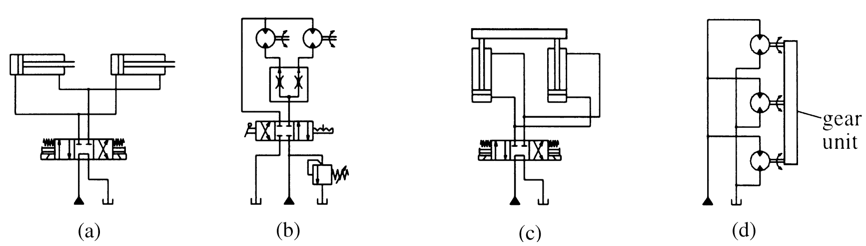

Fig. 8. Hydraulic axes with multiple actuators.

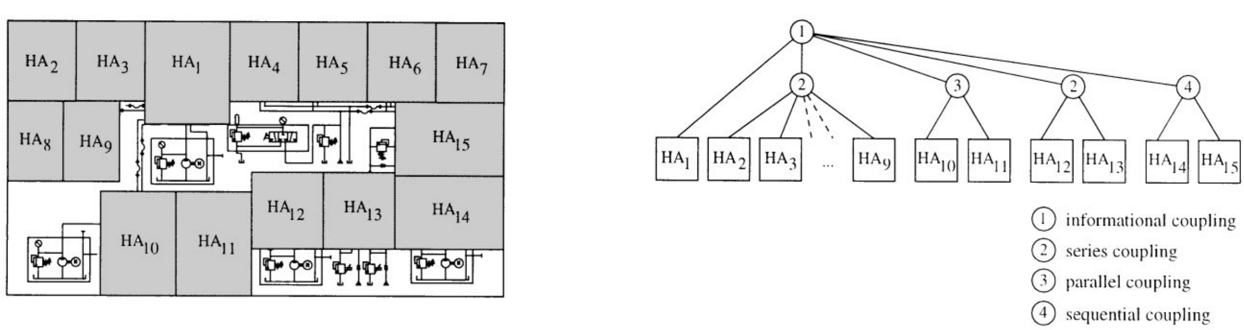

Fig. 9. Overview of the hydraulic axes in the cold-rolling plant (left) and the coupling scheme (right).

extension, and the adaptation of the system (Stein, 1996). The separate treatment of hydraulic axes remarkably reduces the design effort within the following respects:

Smart simulation. Smart simulation is a human strategy when analyzing a complex system: subsystems are identified, cut free, and simulated on their own. This strategy reduces the simulation complexity and simplifies the interpretation of its results. Hydraulic axes establish suited subsystems to be cut free, since they perform an indivisible but complete subtask.

Static design. Information on the hydraulic axes driving concept (open/closed center, load sensing, regenerative circuit, etc.) allows the selection of computation procedures relating the static design (Walter, 1981; Paetzold and Hemming, 1989). Moreover, the application of modification knowledge has to consider the axes' coupling levels.

Control concept selection. The consideration of couplings between input and output variables supplies a necessary decision basis for the selection of control concepts. Analyzing the decouplability matrix $\boldsymbol{D}$ (Schwarz, 1991) yields a common approach here. Note that the system order that can be tackled is limited. The functional structure analysis provides a separation into (1) SISO systems, to which standard methods of controller design can be applied, and (2) coupled subsystems of a reduced order, for which decouplability can be investigated more efficiently or even becomes possible at all.

Diagnosis. Having a hydraulic circuit decomposed into its hydraulic axes, the diagnosis process can focus onto a single axis according to the following working hypothesis: if symptoms are observed merely at a single hydraulic axis, then the defect component(s) must be amongst the components of this axis. If symptoms are observed at several axes, the axes coupling type will give further answers with respect to defect components. Hesse and Stein (1998) describe a system where this idea has been set into operation.

Note that a smart classification of the couplings between hydraulic axes forms the rationale of whether a decomposition of a hydraulic design problem is permissible. While subsystems with level 0 or level 1 couplings can always be cut free, additional information is required for parallel, series, and sequential couplings. Example: Let A, B be two hydraulic axes.

IF	`coupling{A,B} is parallel`
AND NOT	`time-overlap{process{A},process {B}}`
THEN	`separate_design{A,B} is permissible`

IF	`coupling{A,B} is parallel`
AND	`time-overlap{process{A},process {B}}`
THEN	`separate_design{A,B} is prohibited`

Vier (1999) provides a more detailed description of a methodology to assess the separability of the design of particular hydraulic axes.

4. Graph-theoretical analysis of hydraulic drives

Key objective of the topological analysis of a hydraulic drive is the automatic detection of its underlying functional structure, which is reflected by the hydraulic axes along with their couplings.

Note that within the usual design process, hydraulic axes are not used as explicit building blocks. The reasons for this are twofold: (1) it is not always possible to design a hydraulic system in a top-down manner, starting with hydraulic axes, which are refined within subsequent steps; (2) both the experience and the ability of a human designer to automatically derive function from structure enable him to construct a hydraulic system at the component level.

As an aside, the main working document for a designer is the technical drawing, and there is no tradition or standardized method to additionally specify the functional structure of a hydraulic system. This situation emphasizes the need for an *automatic detection* of the desired structural information.

The topological analysis as pursued here is a matter of graph theory, and, in the following, we will fall back on some basic graph-theoretical concepts such as multigraph, path, or connected component. These concepts are used in a standard way, and the main idea of our elaborations can be understood without being an expert in graph theory. At the reader's convenience Section 4.3 provides a short introduction of the used definitions.

4.1. A hierarchy of coupling types

For the coupling types introduced in Section 2.2 we now develop a precise mathematical formulation. In this connection hydraulic circuits are abstracted towards ordinary graphs. The following definition provides a mapping rule which assigns to each circuit C its *related hydraulic graph* $G_{\mathrm{h}}(C)$.

Definition 4.1 (*Related hydraulic graph*). A related hydraulic graph $G_{\mathrm{h}}(C)$ of a circuit C is a multigraph $\langle V_C, E_C, g_C \rangle$ whose elements are defined as follows. (1) V_C is a set of points, and there is a mapping from the set of non-pipe components in C onto V_C. (2) E_C is a set of edges, and there is a mapping from the set of pipe components in C onto E_C. (3) $g : E_C \to 2^{V_C}$ is a function that maps an $e \in E_C$ onto $(v_i, v_j) \in 2^{V_C}$, if and only if there is a pipe between the components associated with v_i, v_j, and if e is associated with this pipe.

Fig. 10 contrasts a hydraulic circuit and its related hydraulic graph. The labels in the graph shall underline that there is a one-to-one mapping between the elements of the graph and the components of the hydraulic circuit.

Remarks. for each circuit C there exists exactly one hydraulic graph $G_h(C)$. Multigraphs instead of graphs must be used here since components of a hydraulic system may be connected in parallel. Notice the following topological simplifications of C: (1) substructures within (directional) valves are contracted to one single point v, hence making all connected pipes incident to v; (2) variations of the topology coming along with valve switchings are neglected; (3) directional information that results from the behavior of the particular hydraulic components is dropped. These simplifications have no effect on the classification of hydraulic axes couplings.

Definition 4.2 (*Coupling types*). Given is a hydraulic circuit C containing two sub-circuits A, B, which realize two different hydraulic axes. Moreover, let $G_h(C) := \langle V_C, E_C, g_C\rangle$, $G_h(A) := \langle V_A, E_A, g_A\rangle$, and $G_h(B) := \langle V_B, E_B, g_B\rangle$ denote the related hydraulic graphs of C, A, and B, respectively.

Level 0 (*No coupling*.) If $G_h(C)$ is not connected, and if $G_h(A)$ and $G_h(B)$ are subgraphs of different connected components in G_h, then the hydraulic axes A and B are not coupled. A and B do not have any physical connection, and thus they can be investigated independently.

Level 1 (*Informational coupling*.) Let $\{e_1, \ldots, e_n\}$ be in E and each e_i associated with a control line within C. If $G_{h'} := \langle V_C, E_C \setminus \{e_1, \ldots, e_n\}, g_C\rangle$ is not connected, and if $G_h(A)$ and $G_h(B)$ are subgraphs of different connected components in $G_{h'}$, then the hydraulic axes A and B are informationally coupled (cf. Fig. 11). Notice that control lines can be realized by means of electrical, hydraulic, or pneumatic lines.

Level 2 (*Parallel coupling*.) Let $P_{w,s}$ be the set of all paths from a working element w to a supply element s that use no edge associated with a control line. Then A and B are coupled in parallel if there exist two nodes, $v_a \in V_A$, $v_b \in V_B$, such that the following conditions hold:

(1) v_a, v_b are associated with a control element.

(2) $\forall_{p \in P_{w,s}} : v_a \in p \cap V_A \sqcup v_b \in p \cap V_B$.

From the engineering point of view this definition states that each of the axes A and B is controlled by its own control element (cf. Fig. 12).

Level 3 (*Series coupling*.) Let $P_{w,s}$ be the set of all paths from a working element w to a supply element s that have no edge associated with a control line. Then A and B are coupled in series, if an axis $X \in \{A, B\}$ and a path $p \in P_{w,s}$ exist such that the following conditions hold:

(1) p is a subgraph of X.

(2) $\exists v \in p \cap V_Y, Y \in \{A, B\} \wedge Y \neq X$: v is associated with a control element.

If several axes are coupled in series, at least one axis controls the flow of all other axes (cf. Fig. 13).

Level 4 (*Sequential coupling*.) A and B are sequentially coupled if the following conditions hold:

(1) A and B have no coupling of type $0, \ldots, 3$.

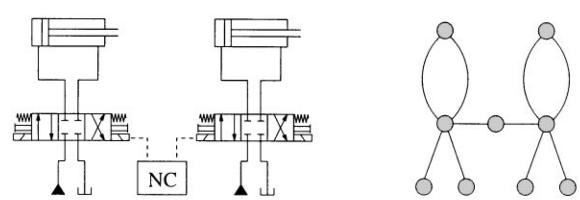

Fig. 11. Circuit with informationally coupled hydraulic axes.

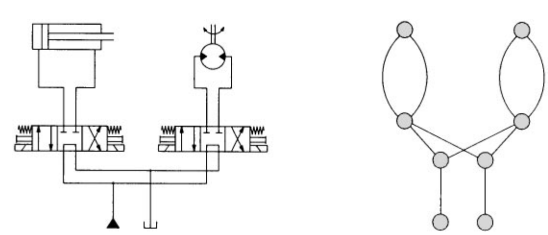

Fig. 12. Circuit containing hydraulic axes coupled in parallel.

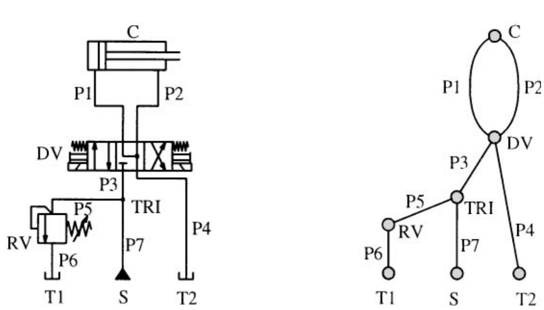

Fig. 10. Sample circuit with its related graph.

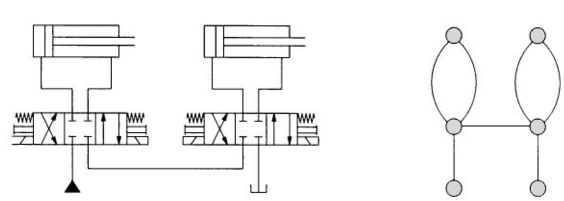

Fig. 13. Circuit containing hydraulic axes coupled in series.

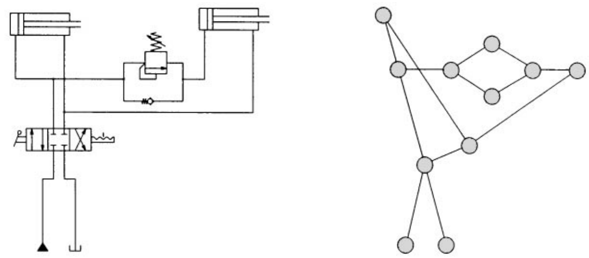

Fig. 14. Circuit containing sequentially coupled hydraulic axes.

(2) A and B establish no equal sub-circuits of C (Fig. 14).

If A and B are equal sub-circuits, they will produce the same behavior and hence together form a single hydraulic axis as described in Section 2.2.

4.2. Operationalizing hydraulic axes identification

The preceding section precisely defines coupling types, but gives only less means of how hydraulic axes and their couplings can be identified in a hydraulic graph. This subsection outlines a procedure that accomplishes this task and that has been realized and tested with a large hydraulic library. A detailed description of the underlying algorithms and concepts can be found in Stein and Schulz (1998).

The analysis procedure comprises three steps: preprocessing, axes identification, and coupling-type determination.

4.2.1. Preprocessing

The preprocessing step starts with an abstraction from a circuit C onto its related hydraulic graph G_h. To reduce G_h's complexity — but, in first place, to make axes identification possible at all, G_h is simplified by means of merging, deletion, and condensation rules. Fig. 15 illustrates the application of such rules.

Among others, the simplification process implies the application of the following rules:

Control path deletion. Control paths establish no isolation characteristic for hydraulic axes. They can be found (and removed) easily in G_h.

Dead branch deletion. A dead branch is a subgraph whose nodes are not associated with control or working elements and whose connectivity is 1 (cf. Fig. 16).

Special component deletion. There exist a few non-auxiliary components, whose corresponding nodes can be removed from G_h without a sophisticated investigation. The check-valve is an example for such a component.

Loop resolution. A circuit may contain cyclic structures or components connected in parallel. These structures are not necessary for detection purposes if they neither contain nor control a working element (cf. Fig. 17).

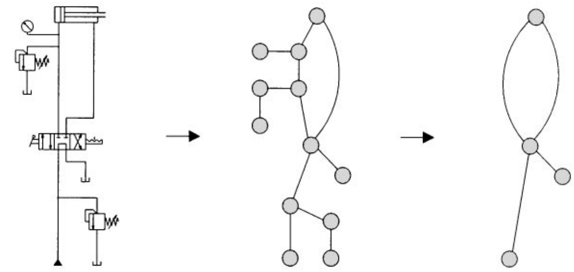

Fig. 15. Example for the abstraction and simplification of a hydraulic circuit.

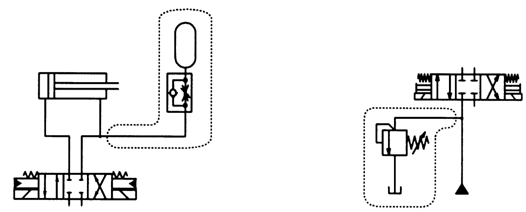

Fig. 16. Two examples for a dead branch.

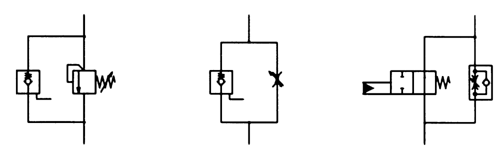

Fig. 17. Examples for loops that can cut.

Note that the valve in the rightmost circuit merely provides an auxiliary function; in its context of usage it cannot control a working element.

These and other rules have been formulated by means of graph grammars (Rosenberg, 1994; Schneider, 1993). Since an arbitrary application of the rules may lead to a sub-optimum simplification of the hydraulic graph, a partial ordering amongst the rules has been defined, which controls rule execution.

The runtime complexity in the preprocessing is dominated by the algorithm for loop detection, which can be assessed with $O(|E|)$ (McHugh, 1990).

4.2.2. Axes identification

Identifying a hydraulic axis means to search for a set of nodes in the hydraulic graph whose counterpart in the circuit realizes a particular function. Each such set must contain at least one working element and one supply element. Moreover, all components that also belong to the hydraulic axis must lie on some path between the working and the supply element. This observation suggests to employ shortest-path algorithms for axes identification; important representatives are Dijkstra's and Floyd's algorithm (McHugh, 1990; Sedgewick, 1992).

To find hydraulic axes, all paths between the supply elements and the working elements of a circuit must be investigated. Hence a shortest-path problem must be solved for each supply element. Each run of the shortest-path algorithm labels the edges in the form of a directed

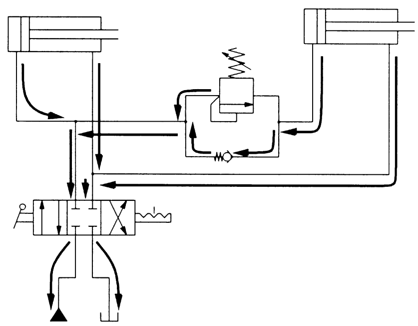

Fig. 18. Circuit with successor information after a shortest-path run.

tree, which encodes a successor relationship between the nodes (cf. Fig. 18).

All components that lie on the same path in the directed tree belong to the same hydraulic axis. Since hydraulic graphs are multigraphs there must exist two different paths from a working element to a supply element. A second path can be found by simply deleting one edge incident to the working element and then applying the shortest-path algorithm again.

The worst-case complexity for axes identification is $O(|V|^2 \cdot |E|)$. Again, a detailed description of this step can be found in Stein and Schulz (1998).

4.2.3. Coupling-type determination

The coupling type between hydraulic axes can only be determined, if all components of a circuit have been assigned to at least one axis. In most cases, coupling-type determination requires the comparison of supply paths between the working elements of the axes. If a circuit contains exactly two axes, every coupling-type can be classified with a search effort of $O(|E|)$.

Given a circuit with n axes, the couplings between *all* axes need to be determined. Using a naive approach, the above search effort is carried out $\binom{n}{2} \in O(n^2)$ times. If, on the other hand, a circuit contains a lot of axes of only one coupling type, a linear number of comparisons is sufficient.

In this connection some kind of transitivity property for coupling types would be useful. In generality, such a transitivity cannot exist. However, given three axes and information on two coupling types, we are able to restrict the third coupling to a subset of all types: let the known coupling types be a and b, $a, b \in \{0, \ldots, 4\}$. Then for the third coupling c the following holds: $c \geq \min\{a, b\}$. Stated another way, a weaker coupling is not possible since the axes are coupled indirectly via the third axis. This property can be exploited to reduce the complexity of the coupling type determination.

4.3. Definitions from graph-theory

This subsection shortly revisits some definitions from graph theory, which have been used in the text. For an in-depth study, the interested reader may refer to relevant literature (e.g. Cormen et al., 1990; Jungnickel, 1990; McHugh, 1990).

1. A *multigraph* G is a triple $\langle V, E, g\rangle$ where $V, E \neq \emptyset$ are finite sets, $V \cap E = \emptyset$, and $g : E \to 2^V$ is a mapping, with $2^V = \{U \mid U \subseteq V, |U| = 2\}$. V is called the set of points, E is called the set of edges, and g is called the incidence map.
2. A graph $H = \langle V_H, E_H, g_H\rangle$ will be called a *subgraph* of $G = \langle V, E, g\rangle$, if $V_H \subseteq V$, $E_H \subseteq E$, and g_H is the restriction of g to E_H. A subgraph will be called an *induced subgraph* on V_H, if $E_H \subseteq E$ contains exactly those edges incident to the points in V_H. For $T \subset V$, $G \setminus T$ denotes the subgraph induced on $V \setminus T$.
3. A tuple $(e_1, \ldots, e_n)$ will be called a *walk* from v_0 to v_n, if $g(e_i) = \{v_{i-1}, v_i\}$, $v_i \in V$, $i = 1, \ldots, n$. A walk will be called a *path*, if the v_i are mutually distinct. Instead of using a tuple of edges, a walk may also be specified by a tuple of points, $(v_0, \ldots, v_n)$.
4. G will be called *connected*, if for each two points $v_i, v_j \in V$ there is a walk from v_i to v_j. If G is connected and $G \setminus v$ is not connected, v establishes an *articulation point*. The maximum connected subgraphs of G are called *connected components*.
5. $\kappa(G)$ is called the *connectivity* of G and is defined as follows. $\kappa(G) = \min\{|T| : T \subset V \text{ and } G \setminus T \text{ is not } \textit{connected}\}$. G is called *k-connected*, if $\kappa(G) \geq k$.

Fig. 19 illustrates the definitions.

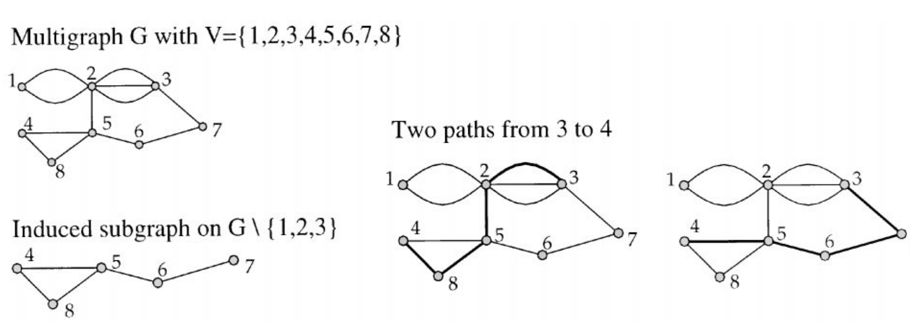

Fig. 19. Illustrations of graph definitons.

5. The role of structural information in $^{\text{art}}$*deco*

Circuit design as carried out by a designer happens within the following steps: (1) demand interpretation, (2) sketch of a first solution, (3) check of the draft circuit with respect to syntactical, geometrical, logical, and dimensional constraints, and (4) design modification and refinement.

The basic idea of $^{\text{art}}$*deco* is not to replace this procedure, but to support it as far as possible. In $^{\text{art}}$*deco*, components are selected, arranged, connected, dimensioned, and simulated while the model formulation process is made transparent. The information that is necessary for the checking and simulation process is derived from the drawing (Stein, 1995). E.g. while drawing a line between two components' gates the appropriate pipes are instantiated; during simulation $^{\text{art}}$*deco* detects, schedules, and processes events caused by discontinuous component state changes such as from relief valves that may open or shut. Fig. 20 depicts snapshots when working in edit and simulation mode, respectively.

During simulation, the user is allowed to trigger events by operating components like switches or valves. The related models are updated immediately in the background, thus providing the feeling of interacting with a running system.

Essentially, $^{\text{art}}$*deco* exploits the structural information within the following respects:

1. *Model synthesis*. The position of cylinders and way valves, or the state of relieve valves directly influences the model synthesis process. By a topological analysis during model synthesis, $^{\text{art}}$*deco* excludes physically contradictory model combinations at the outset (Stein et al., 1998).
2. *Formulation of design knowledge*. Stein and Vier (1998) present a design language tailored to fluidic circuit design. Their approach aims at the improvement and adaptation of preliminary circuit designs: design knowledge is formulated by means of modification rules, which, in turn, consist of an action specifier (What shall be done?) and a location specifier (Where shall it be done?). To make modification rules a working concept, it is vital to know both, which components belong to which axis and how axes are coupled.
3. *Focused analysis*. Section 3 lists analysis situations that benefit from an isolated investigation of crucial circuit parts.$^{\text{art}}$*deco* cannot automate the mentioned tasks but forms a necessary prerequisite by detecting and isolating a circuits' hydraulic axes.

Compared to other component-oriented, hydro-static simulation tools such as OHCS (Nakashima and Baba, 1989), Bath*fp* (Tilley et al., 1991), DSH*plus* (Kett, 1993), HOPSAN (Krus et al., 1991), ITI-SIM (Großmann and Uhlig, 1996), or MOSIHS (Piechnick and Feuser, 1994), the utilization of structural information as pursued by $^{\text{art}}$*deco* goes beyond the current simulation technology.

6. Conclusion and current research

The contributions of this paper are twofold. (1) It discusses the role of structural information when designing hydraulic control systems, and (2) it provides both a systematics and theoretical foundations for the automatic detection of the functional structure given a hydraulic circuit diagram.

The effort in formalizing and detecting structural information is justified. Structural information is a prerequisite when operationalizing hydraulic design knowledge within a knowledge-based system. In particular, knowledge about the system's hydraulic axes along with their couplings can be exploited during simulation,

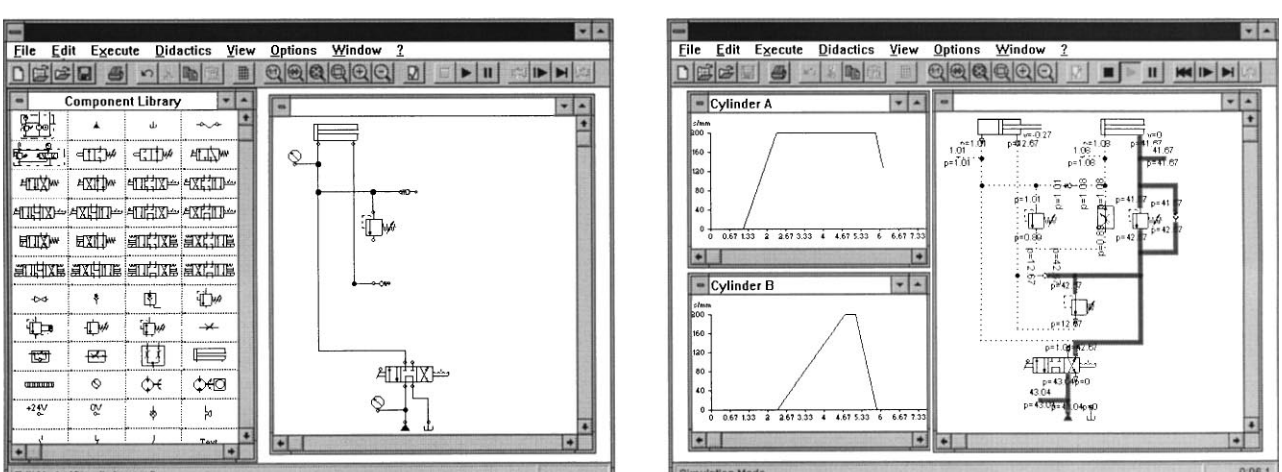

Fig. 20. The snapshot on the left-hand side shows a part of the component library and a circuit currently edited. The snapshot on the right-hand side shows a simulation run and the cylinders'related distance/time diagrams.

demand interpretation, control concept selection, circuit diagram modification, and diagnosis tasks.

Related to this paper, our current research covers the following core aspects:

Formalization of design knowledge. Those parts of a human expert's design knowledge that explicitly refer to structural information are identified and formalized with respect to their processing within our design and analysis environment ^{art}*deco*. The two rules, shown in Section 3, represent a small example for this kind of knowledge.

Case-based design of hydraulic systems. Hydraulic axes establish suited building blocks when automatically constructing new systems by means of case-based reasoning (CBR). Based on this idea we have developed a prototypic design assistant, which enables a user to formulate his design ideas at the functional level. A case-base is searched for hydraulic axes fitting best the specified function, and, in a subsequent step, these building blocks are automatically scaled and composed towards a new system (Stein, 2000).

References

Cormen, T.H., Leiserson, C.E., Rivest, R.L., 1990. Introduction to Algorithms. MIT Press, Cambridge, MA.

Ebertshäuser, H., 1994. Grundlagen der hydraulischen schaltungstechnik. O + P Ölhydraulik und Pneumatik 38 (10), 604–607.

Föllinger, O., 1992. Regelungstechnik, Vol. 7. Hüthig, Heidelberg.

Großmann, K., Uhlig, A., 1996. Von der hydrauliksimulation zur systembewertung. O + P Ölhydraulik und Pneumatik, 40 (11–12), 766–770.

Hesse, T., Stein, B., 1998. Hybrid diagnosis in the fluidic domain. Proceedings of the EIS 98, International ICSC Symposium on Engineering of Intelligent Systems, University of La Laguna, Tenerife, Spain, February.

Jungnickel, D., 1990. Graphen, Netzwerke und Algorithmen. BI Wissenschaftsverlag, Wien, Austria.

Kett, R., 1993. Ein Plus für DSH. O + P Ölhydraulik und Pneumatik, 37 (6), 517–523.

Krus, P., Jansson, A., Palmberg, J.-O., 1991. Real-time simulation of hydraulic control systems with complex mechanical loads. In: IFAC Symposium on Computer Aided Design in Control Systems, Vol. 1. Swansea, UK, pp. 538–544.

McHugh, J., 1990. Algorithmic Graph Theory. Prentice-Hall, Englewood Cliffs, NJ.

Nakashima, Y., Baba, T., 1989. OHCS: hydraulic circuit design assistant. In: Proceedings of the First Annual Conference on Innovative Applications of Artificial Intelligence. Stanford.

Paetzold, W., Hemming, W., 1989. Hydraulik und Pneumatik. Christiani, Koblenz, Germany.

Piechnick, M., Feuser, A., 1994. Simulation mit Komfort — HYVOS 4.0 und MOSIHS 1.0. O + P Ölhydraulik und Pneumatik 38 (5), 270–275.

Rosenberg, A.L., 1994. Issues in the Study of Graph Embedding. Technical Report, IBM Thomas J. Watson Research Center.

Schneider, H.J., 1993. On categorical graph grammars integrating structural transformations and operations on labels. Theoretical Computer Science 109, 257–274.

Schwarz, H., 1991. Nichtlineare Regelungssysteme — Systemtheoretische Grundlagen. Oldenbourg, München.

Sedgewick, R., 1992. Algorithms in C + +. Addison-Wesley, Reading, MA.

Stein, B., 1995. Functional Models in Configuration Systems. Dissertation, University of Paderborn, Department of Mathematics and Computer Science.

Stein, B., 1996. Optimized Design of Fluidic Drives — Objectives and Concepts. Technical Report tr-ri-97-189, University of Paderborn, Department of Mathematics and Computer Science, August.

Stein, B., 2000. How case-based methods can automate fluidic circuit design. In: Proceedings of the First Fluid Power Net International (FPNI) Ph.D. Symposium Hamburg, Germany, to appear.

Stein, B., Curatolo, D., Hoffmann, M., 1998. Simulation in FluidSIM. In: Fachausschuß 4.5 der GI ASIM Arbeitsgemeinschaft Simulation, editor, SiWis '98. Workshop "Simulation in wissensbasierten Systemen", 61, Paderborn, April. Fachgruppe 4.5.3 "Simulation und Künstliche Intelligenz" der Gesellschaft fr Informatik.

Stein, B., Schulz, A., 1998. Topological Analysis of Hydraulic Systems. Technical Report tr-ri-98-197, University of Paderborn, Department of Mathematics and Computer Science, July.

Stein, B., Vier, E., 1998. An approach to formulate and to process design knowledge in fluidics. Recent Advances in Information Science and Technology. Second Part of the Proceedings of the Second IMACS International Conference on Circuits, Systems and Computers, CSC '98. World Scientific, London.

Tilley, D.G., Richards, C.W., Tomlinson, S.P., Burrows, C.R., 1991. Role of simulation in the design of fluid power systems. In: IFAC Symposium on Computer Aided Design in Control Systems, Vol. 1. Swansea, UK, pp. 561–566.

Unbehauen, H., 1994. Regelungstechnik, Vols. I–III. Vieweg, Braunschweig, Germany.

Vier, E., 1996. Rechnergestützter Entwurf geregelter fluidischer Antriebe. Forschungsbericht 3/96, MSRT, Universitt Duisburg.

Vier, E., 1999. Automatisierter Entwurf geregelter hydrostatischer Systeme. Fortschritt-Berichte VDI. Reihe 8. Vol. 795 VDI, Düsseldorf, Germany.

Vier, E., Lemmen, R., Schwarz, H., 1996. Support for hydraulic control system design — an approach with applications in marine technology. In: Conference on Circuits, Systems and Computers '96, Hellenic Naval Academy, Athens, Greece.

Walter, H., 1981. Auslegung einer Hydraulikanlage. O + P Ölhydraulik und Pneumatik 25 (9), 692–701.

Wessling, B., 1995. Modern design of cold rolling mills for stainless steel. In: Technologies for the Enhancement of Rolling Mills and Processing Lines. Mannesmann Demag AG, Ratingen, pp. 71–78.

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