Analysis and optimization of compressed air networks with model-based approaches

Susanne V. KRICHEL, Oliver SAWODNY

Abstract: Compressed air is one of the basic energy sources in several industrial areas. It is used during manufacturing processes, commonly as driving force for actuating pneumatic cylinders and in power tools such as pneumatic screwdrivers. The widespread use of compressed air justifies efforts to reduce losses within its infrastructure. The two main loss sources are the consumption of electrical energy for the production of compressed air and the distribution through piping networks with non-negligible leakage effects and pressure drops. In order to reduce losses and optimize the generation and transport of compressed air, model-based approaches are used. The paper presents dynamic models for highlighted network components. Two applications of those models on an abstract level are under research for (1) leakage detection and (2) topological network optimization. The work presents our progress as part of project EnEffAH.

Keywords: compressed-air networks, component modeling, leakage detection, topology optimization, simulation, pressure measurements

1 Introduction

The efficient usage of energy resources in production processes is nowadays one of the primary business goals in modern companies. Reference [1] states that a considerable percentage of the total European electrical energy consumption goes to the production of compressed air. Therefore, novel engineering concepts are required to enhance the efficiency of the compressed air infrastructure consisting of generation, distribution and application. In order to study the potential of efficiency improvements in that area, the Institute for System Dynamics, University of Stuttgart, joined efforts with industrial partners, and takes part in the project EnEffAH. The project is aimed at reducing energy losses in both pneumatic and electrical systems using simulations and system theory techniques. Model-based simulations of the pneumatic infrastructure support a better understanding and help both identifying and quantifying saving potentials.

The project focuses not only on minimizing the consumption by optimizing drive applications or reducing leakage losses and pressure drops (bottom-up approach) but also to enhance the efficiency by studying the generation part (top-down approach). Design and dimensioning of drive applications is currently done with simulation programs, aiding choice of components in size and type, computation of controller parameters and allowing more accurate prediction of energy costs [2]. Simulation programs require dynamic models for physical components that represent both their steady-state and transient behaviour. A lot of

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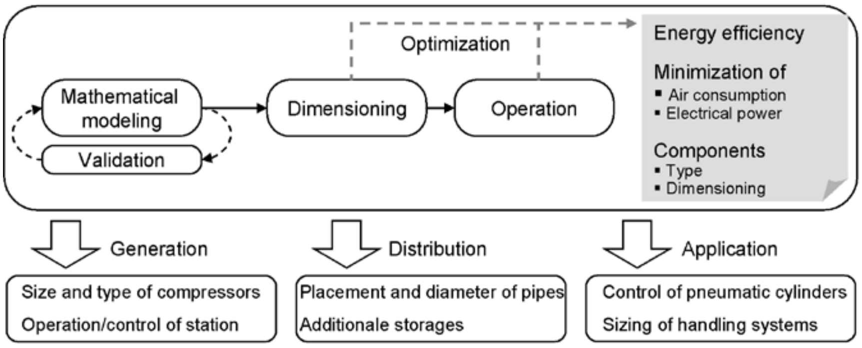

Figure1. *Research areas of project EnEffAH: generation, distribution and application with generalized model-based optimization tool chain applied to each sub-group.*

research has been done on efficient design and operation of water or pipeline networks using mathematical procedures. Even if the generation and distribution are stated to offer the highest and easy achievable saving potential, theoretical analysis of compressed air networks has not been a priority so far. Aspects such as leakage losses, dimensioning of pipes and low-energy generation of compressed air are currently under active research [3]. The detailed mathematical description of pneumatic drive components might be a reasonable approach for machine design and small networks, but it is inadequate for large industrial-grade networks. By implementing different model-based analysis approaches, the challenges and prospects of system theory within the framework of efficiency improvements are studied in this paper. The focus is here in the detection/reduction of leakage losses, the optimization of the generation unit and the development of monitoring concepts for compressed air networks. The model-based approach is schematically presented in *Figure 1*.

The paper is structured as follows: Section 2 lists selected modeling approaches for compressed air network components under different levels of abstraction. Novel modeling approaches for oil-injected screw compressors and long pneumatic tubes are referenced. In Section 3.1, an abstract network model is shown based on electrical analogies. It is studied in Section 3 under system theory aspects such as parameter sensitivity, operating point accuracy and dynamic behaviour of its states. First, a leakage detection algorithm is implemented based on an extended Kalman filter and evaluated in Section 3.2. Second, the abstract network model is presented as basis for our current research on model-based topology optimization of compressed air networks in Section 4. A detailed conclusion is given in Section 5 with an outlook into future research.

2 Modeling of compressed-air network components

For the implementation of system theory concepts such as model-based fault diagnosis and isolation (FDI) techniques [4], the use of the signal-flow oriented simulation program Matlab/Simulink is chosen here. Further details on this kind of simulation software compared to object-oriented ones are given in [5], [6]. Two main variables for describing pneumatic systems are pressure p and mass flow rate $\dot{m}$. In the following, selected network components are listed and described by simplified models. Different levels of abstraction are chosen for changing simulation requirements.

2.1 Generation units

Generation models include the modeling of one or several compressors, the air treatment unit and the central storage. The goal of the generation in a compressed air network is a) to deliver the consumed air instantly and b) to keep the pressure level everywhere constant within a defined pressure band, but as small as possible. To study the efficiency of each compressor and the station itself, dynamic models are developed. Previous work within the EnEffAH project dealt with the derivation of a dynamic model for oil-flooded screw compressors [2]. The model represents in detail the thermodynamic, electrical and mechanical parts. This model is currently used for detailed study of loss sources within one compressor block and an optimization of the operational strategy in general. Simpler models consider the fact that most compressors are running in on/off strategy [6]. Nowadays, compressor stations consists of a mix of several compressor types that are able to deliver as much mass flow as needed within a reasonable time delay dependent on the overall control. This can then be either represented simply by an unlimited mass flow model or by a PI-controller for the pressure within the storage. The input is the pressure in the storage and its output is a limited mass flow. The air treatment unit is not considered in the following but can be split into two models: filters cause a pressure drop in the system; dryers mainly cause a loss of air flow. They are modeled as resistance and consumer, respectively. Storage is placed after the compressors and air treatment unit to a) buffer high-dynamic pressure changes in the network and b) to keep some reservoir in case of failure of the production system. The air temperature T_S within the volume is normally assumed to be constant (isothermal behaviour). The complete dynamic equations for pressure p_S and temperature T_S look as follows

$$\dot{p}_S(t) = \frac{nR}{V_S}(T_{prod}\dot{m}_{prod} - T_{cons}\dot{m}_{cons}), \quad \dot{T}_S(t) = = \frac{nRT_S}{p_S}\left(\left(T_{prod} - \frac{T_S}{n}\right)\dot{m}_{prod} - \left(T_{cons} - \frac{T_S}{n}\right)\dot{m}_{cons}\right) \tag{1}$$

with R as general gas constant, $\dot{m}_{cons}$ as consumed mass flow, $\dot{m}_{prod}$ as produced mass flow, n as polytropic coefficient and $T_{cons/prod}$ as temperature of mass flow rates (with $T_{cons} = T_S$ for most applications).

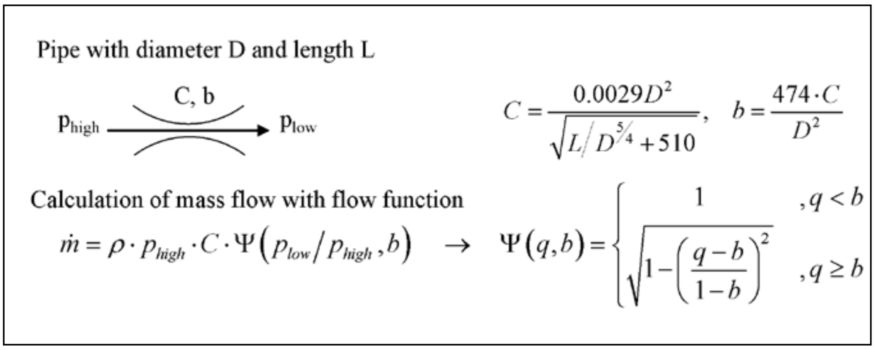

Figure 2. *Simplified model for pneumatic transmission lines based on C,b-values and throttle-like flow characteristic.*

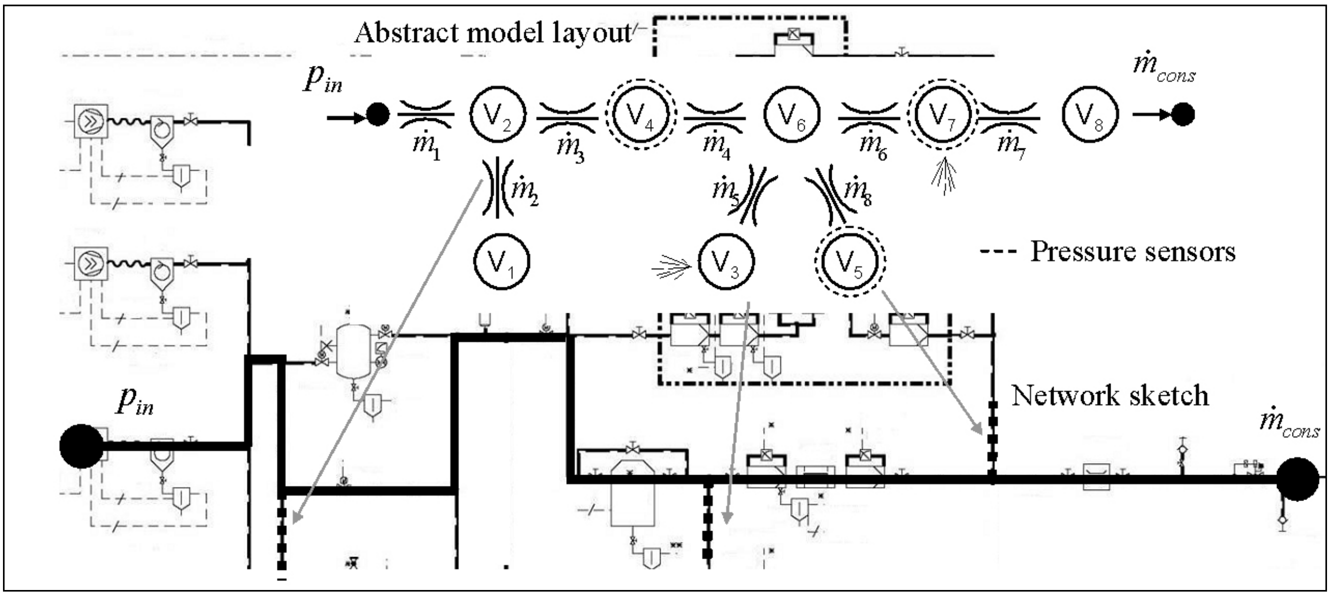

Figure 3. *Network plan of the real pneumatic test network and a graphical sketch of the abstract model chosen for a certain path through the network (8 volumes and 8 throttles).*

2.2 Distribution elements

Distribution models include modeling of fluidic transmission pipes of varying sizes (from small tubes within drive application with a diameter of down to 4mm to big pipes of a diameter up to 120mm) and lengths. Additionally, pipes are connected by armatures (represented by their equivalent length L_{eq}) [15]. Pipes are typically modeled as simple pneumatic resistances (similar to valves) with sonic conductance *C* and critical pressure ratio *b* according to [7]. There exist several formulas that compute the *C,b*-values dependent on the length *L* and the diameter *D* of a pipe [8] (see *Figure 2*).

That simple model covers one of the four characteristics of a transmission line, namely the pressure drop dependent on the flow rate. Further characteristics as dead volume of the pipe, limited speed of the pressure waves and reflection of the pressure waves inside the pipe are neglected. A numerically stable model for signal-flow oriented simulation programs based on the exact partial differential equations from fluid dynamics has been implemented in previous works [9]. It uses a combined semi-discretization and control-volume method to solve the equations and is applied for the detailed simulation of pneumatic applications. The model is of low order but not applicable to high-dimensional network models. The usage of the *C,b*-values makes it easy to connect several elements of a network together by either series or parallel connections.

3 Abstract network models for leakage detection

With the presented components from Section 2, large network models (considering all pipes, armatures, consumers and the generation unit) are set up. The easiest way to do that is in an object-orientated simulation software such as Dymola. An example network has been chosen and modeled in Dymola.
The network consists of pipes with diameters between 28-54mm and lengths between 0.6 and 6m. There are additionally several armatures such as bends 90°, 120° and dead volume branches that are not listed here explicitly. The network plan is shown in *Figure 3* accordingly with the chosen measurement path in thick black lines. The implementation in Dymola leads to approximately 2000 equations that are automatically simplified by DASSL solver. The pure dynamic equations are not accessible. A nonlinear model of order 2000 cannot be used for model-based approaches due to complexity. As the states should be still related to physical values such as pressure and mass flow, model reduction algorithm are hard to apply. The idea is to represent the dynamics of the system by only volume and throttle elements. Therefore, 8 volumes and 8 throttles are connect to each other. For a validation of the model, measurements are captured. Pressure is measured at three positions marked in the model graphics by dashed circles.

3.1 Abstract network model

The above shown network model is represented by differential equations for the pressure in the volume elements dependent on mass flow through the connecting throttles (according to Eq. (1) and Fig. 2). The dynamic representation is given by 8 states, each for one volume element. Input variables are measured values for the pressure pin and the consumed mass flow $\dot{m}_{cons}$. The output variables are the measured values for $p_{4,5,7}$. The model is thus represented by the following equations $\dot{\vec{p}} = f\left(\vec{p}, p_{in}, \dot{m}_{cons}\right)$ with initial conditions $\vec{p}(t_0) = \vec{p}_0$. The first 3 differential equations are given in Eq. (2). The missing 5 differential equations are derived analogously.

$$\begin{aligned}
\dot{p}_1 &= RTV_1^{-1}\dot{m}_2\left(p_2, p_1\right)\\
\dot{p}_2 &= RTV_2^{-1}\left(\dot{m}_1\left(p_{in}, p_2\right) - \dot{m}_2\left(p_2, p_1\right) - \dot{m}_3\left(p_2, p_4\right)\right)\\
\dot{p}_3 &= RTV_3^{-1}\dot{m}_5\left(p_6, p_3\right)\\
\dot{p}_4 &= RTV_4^{-1}\left(\ldots\right)
\end{aligned} \tag{2}$$

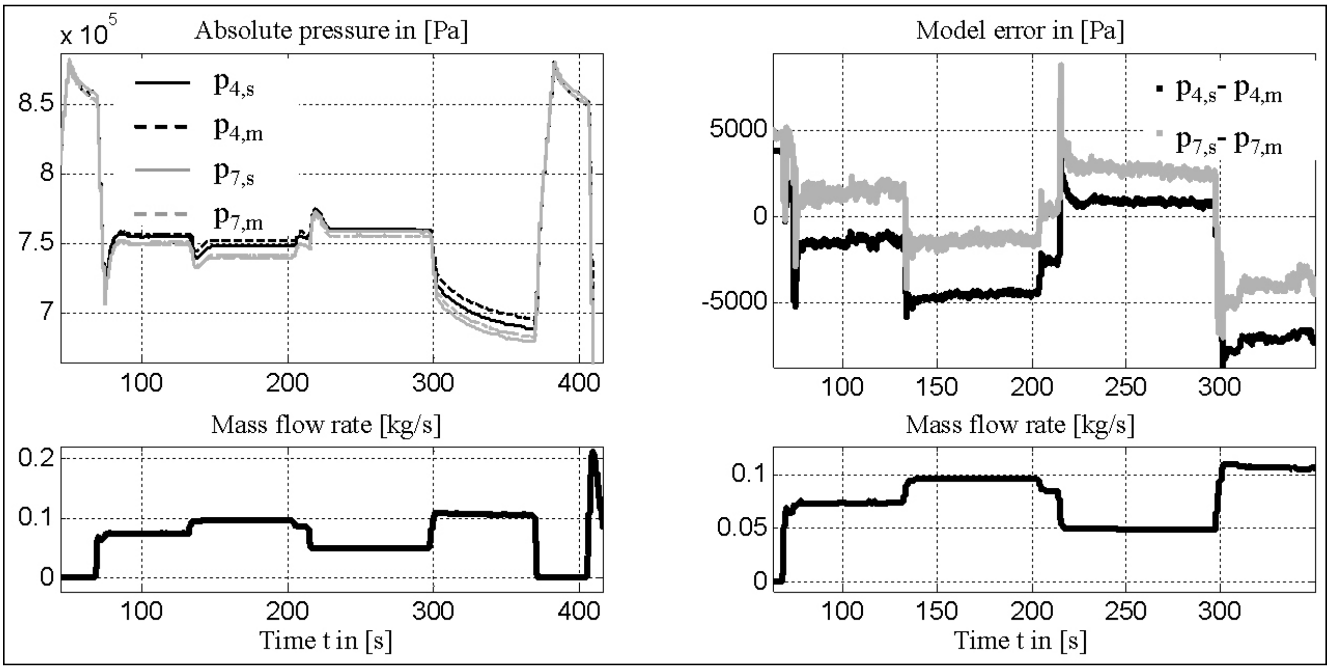

Figure 4. *Validation of model applying several operating points by changing the value of the consumed mass flow. The left graph shows the measured (index m) and simulated (index s) pressure 4 and 7. The right plot shows the deviation.*

The system's equations (2) are now simulated in Matlab/Simulink. Simulation results can be seen in the next section.

3.2 Validation of network equations

For a validation of the abstract model, real measurements are captured in an industrial installation. The consumer is represented by a throttle valve whose opening area is changeable to re-enact varying consumers. Both pressure p_{oil} and consumed mass flow are taken as input to the system. Missing parameters that have to be determined for the model are the volumes and the conductance for each throttle. The critical pressure ratio b for each throttle is set constant with a value of 0.3. The volumes are determined by adding the inner volumes of all pipes and bends that are represented by one volume. The throttle values are chosen such that the steady-state behaviour of the model fits to the measurements.

There are two questions that have to be answered first: a) Are the chosen conductance values valid for several operating points of the system? and b) How sensitive is the system to wrongly estimated parameter values? The answer to the validity of the model for several operating points is given by the plot in *Figure 4*. It is apparent that one set of conductance values is not valid for several set-points. That implies for further studies that either the given (non-) accuracy is acceptable for the planned analysis or the model cannot be used. By aggregating several pipes and armatures together, one throttle *C*,*b*-value model cannot model all nonlinear effects.

Under the assumption of an adequate set of parameters, equation (3) is studied for its sensitivity: how much do the states change if one parameter is wrongly estimated? A full sensitivity analysis $d\vec{p}/d\vec{\theta}$ for the parameters $\vec{\theta} = \left(C_{1\ldots8}, V_{1\ldots8}\right)$ is not given here. Instead, the steady-state (called ss) of the system is determined given fixed input values. The change in the parameters is then approximated by

$$\Delta\vec{p} = \vec{p}_{ss}\left(\vec{\theta}, p_{in}, \dot{m}_{cons}\right) - \vec{p}_{ss}\left(\vec{\theta} + e_i\theta_i, p_{in}, \dot{m}_{cons}\right) \qquad (3)$$

where e_i is the i-th unit vector. The parameter C_4 is changed by 5% of its original value. The states change immediately by 0.04 bar. This means that the system is highly sensitive to parameter changes. A short summary so far concerning the derived model: Pneumatic systems are highly nonlinear due to the characteristics of pneumatic resistances. The dynamics of the system is called stiff as it covers both high dynamic and slow dynamic parts. The aggregation of several components to one throttle model leads to operating point dependent deviations from measurements.

Now, an observer-based analysis is implemented to test the prospects of model-based approaches for pneumatic networks based on the simplified model. The observer is implemented within the framework of fault detection and isolation strategies. For that, a nominal model is needed, where no error occurs. By comparing simulation results to measurements, deviations are interpreted as errors, e.g. parameter offsets or leakage effects. The idea is to implement a leakage detection algorithm for the network. There are two possible places where leakage could be enforced in the industrial network (see Fig. 3, volume 3 and 7). The ansatz is to detect the leakage based on a nominal model. The implementation is shown in the next section.

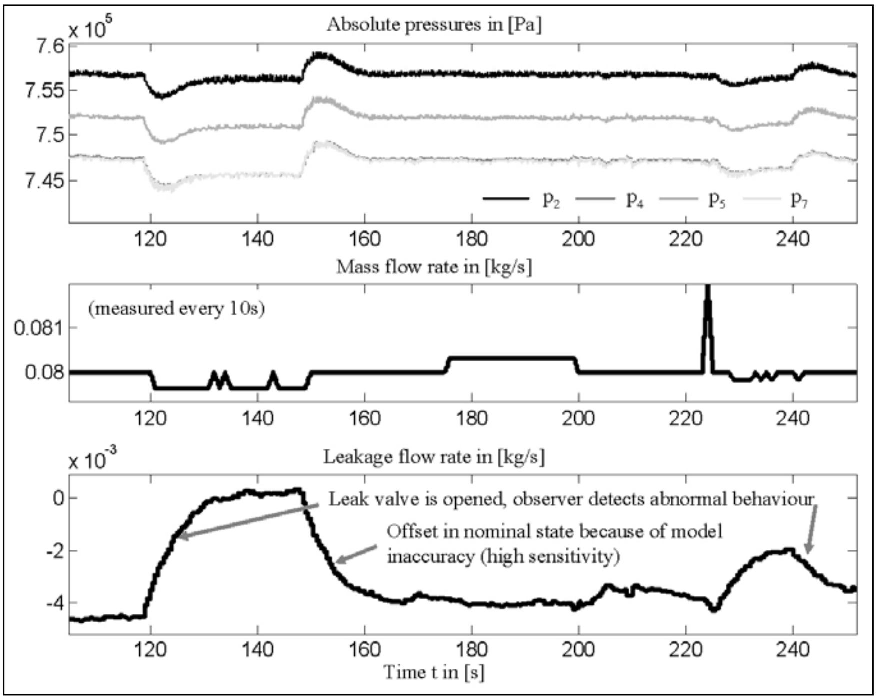

Figure 5. *Results of extended Kalman filter used to detect leakage (estimated leakage is shown in plot at the bottom).*

3.3 Implementation and results of observer-based analysis

With the mathematical formulation of an observer for the Eqs. (2), leakage detection is implemented. Reference [10] shows the derivation of an extended Kalman Filter approach for nonlinear systems. The idea of an observer is the reconstruction of the states by knowing the inputs and measuring some or a combination of system's states. If the right combination of states for the measurements is chosen, the system will be called observable. The possible leakage is added to the system as an additional state whose value has to be estimated changing over time. The dynamic equations are updated as follows (not shown state equations stay unchanged):

$$\dot{p}_3 = RTV_3^{-1}\left(\dot{m}_5\left(p_6, p_3\right) - \dot{m}_L\right), \quad \frac{d\dot{m}_L}{dt} = 0. \tag{4}$$

The new state $\dot{m}_L$ represents a leakage at V_3 that is constant in each time step dt. The system is observable with the measured pressures. *Figure 5* shows the results of the implemented Kalman filter. The system starts in a nominal operating point with a good choice of parameters. At two time steps leakage is applied by opening an exhaust valve. The observer estimates the deviations from the simulated states into the leakage state. Fig. 5 shows that a leakage is detected but that there is also an offset in the nominal state. The reasons are a) the chosen parameter set is valid but not 100% accurate such that all model errors are estimated into the additional state and b) in the real network there were small leakages that couldn't be erased totally before the testing. The strategy still works if there are two leaks in the systems as the system is still observable.

3.4 Challenges with sensor accuracy

There are several challenges when applying system theory approaches in practice to compressed air networks: a) Pressure sensors have a limited accuracy. The network examined above had pipes of small diameters. Pipes within huge industrial networks are up to 120mm in outer diameter. Thus, the pressure drops decrease. Standard industrial sensors are not too expensive but suffer from a lack of accuracy. In simple experiments, the real accuracy of pressure sensors was tested: with standard flow sensors, pressure drops around 1000 Pa can be captured. b) Access points for pressure sensors are normally equally distributed over an existing network. To apply above shown strategies, mass flow sensors measuring the consumption are obligatory. The system has to be split into smaller network parts; otherwise the system's accuracy is too low. Mass flow sensors are either very expensive or difficult to install. Without knowing the mass flow of the consumers, leakage detection strategies are infeasible due to the lack of good and simple nominal models. The sensor placement is also important for model-based analysis. The implementation of a model-based observer requires a good choice of measurements spread over the network. There exist rating numbers that help determining the rate of observability to determine where the pressure sensor should be placed. c) During audits, pressures are monitored automatically every 10 seconds to 1 minute. As the dynamics of the pneumatic systems is very stiff, model-based approaches require a sampling rate of at least less than 100 Hz. The resolution of the data capturing system has to be high as well to not loose detail. d) Furthermore, pressure sensors are widespread within the network. Thus, a special measurement system based on Phoenix Contact hardware (Axioline components) and Bluetooth wireless transmission was installed for the leakage detection. The data is sampled with 30ms and a data conversion of 12bit, which is sufficient to capture the data rapidly and accurately.

■ 4 Application: Topology optimization for efficiency improvements

One of the current research topics within the EnEffAH project deals with the development of a novel algorithm for optimizing the structure of compressed air networks. The information about how network installations in real life are done is rare. But

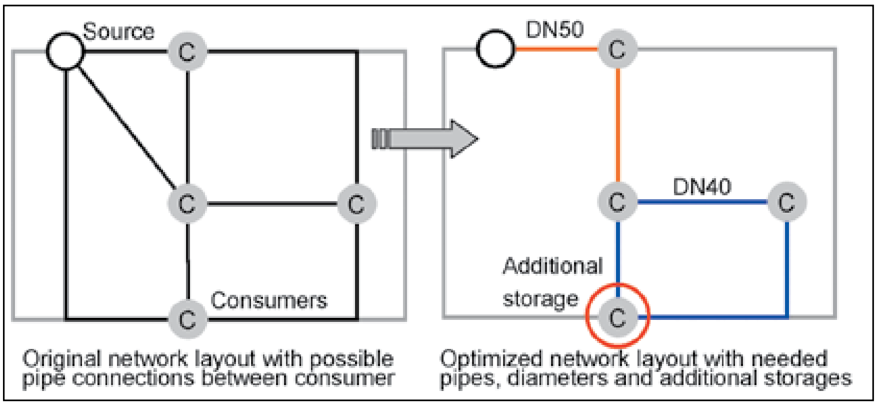

Figure 6. *Schematic sketch of network optimization tool: based on a network structure with all possible pipes between consumers C, the optimization determines which pipes are needed and which diameters has to be used. Additionally, storages are placed within the network for robustness.*

often, application engineers define the network parameters by experience. Previous research in determining an optimal design of networks based on mathematical algorithms was mostly done for water networks or huge nationwide gas networks [11]. Project EnEffAH aims at adapting those methods to topology design of compressed air networks. Three main aspects are covered: a) where do pipes have to be installed to guarantee an optimal supply of air to all consumers, b) what is the optimal diameter for each pipe with regard to low pressure drops over the network and c) where do additional storages have to be placed to handle consumption variations and make the network more robust. The focus of the new algorithms is the simultaneous topology and size optimization of the network, i.e. placement and diameter of each pipe. In Fig. 6 the schematic sketch of a small industrial network with 4 consumers "C" and 8 possible pipe connections is shown. The right side of the figures presents the optimized network configuration and the location of the additional storage. Abstract network models similar to the ones from Section 3 are used to represent the overall network structure and behaviour. The optimization problems arising from goal definitions a)-c) is a highly nonlinear, combinatorial optimization problem with discrete decision variables for diameters and storages (called Mixed-Integer nonlinear optimization problem). Hence, it is solved based on the theory of genetic algorithms [12, 13]. The network is considered to be represented both by static and dynamic equations [14]. The placement of additional storages requires dynamic models whereas topology design is based on static models. The algorithms solve the problem by accounting for the following constraints: minimum supply pressure requirements for each consumer based on consumption profiles, installation costs based on real cost calculations (pipe material, labour costs, installation environment), reliability of the network (in case of failure), and robustness in pressure changes against sudden consumption variations. The developed algorithms are validated against already planned networks.

5 Conclusions

The reduction of energy losses within the pneumatic infrastructure is a highly-motivated research area. This work focuses on the application of model-based approaches such as the implementation of an extended Kalman filter or the topology optimization. The goal is to develop novel engineering concepts which lead to a better understanding of the loss sources and possible improvement strategies. After giving an introduction into modeling techniques for compressed air components, an abstract network model based on volumes and pneumatic resistance elements was developed. By using this approach it was possible to derive a model of low order with which further analysis strategies could be implemented. Pneumatic models are shown to be highly sensitive to parameter changes. The stiffness of the system enforces tightened requirements to the usage of simulation programs and ODE solvers. The results based on the implemented observer showed that FDI strategies could be implemented successfully. But, the amount of information coming from the results was mainly dependent on the sensor accuracy and the fluctuation of operating points during the diagnosis process as both complicate the interpretability. The modeling of pneumatic networks leads always to a trade-off between accuracy (modeling of each component, high complexity) and coverage (modeling the overall dynamic behaviour, low accuracy). The abstract network models are used for a further application, namely the optimized topology design of compressed air networks. The main assumptions and goals of this current research work are shown. In this paper we have demonstrated a practical way to simulate compressed air network behaviour. Using these results for the design of realistic system analysis strategies is non trivial, as shown in the paper, but it was demonstrated that model-based analysis strategies such as observers can be designed and abstract models used for further optimization. They were evaluated through simulation and validated with measurements, enabling in future new theory-based analysis techniques to be implemented economically and helping save energy in large scales.

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Modelni pristop pri analizi in optimizaciji pnevmatičnih vezij

Razširjeni povzetek

Stisnjeni zrak je eden izmed osnovnih virov energije na mnogih industrijskih področjih. Uporablja se v proizvodnih procesih kot gonilna sila za pnevmatične valje in v pogonskih orodjih, kot npr. pri pnevmatičnih izvijačih. Široka uporaba stisnjenega zraka vzpodbuja k zmanjševanju izgub znotraj pnevmatične infrastrukture. Glavna izvora izgub sta poraba električne energije pri proizvodnji stisnjenega zraka in izgube pri distribuciji stisnjenega zraka po pnevmatičnem omrežju z neizogibnim puščanjem in padci tlakov. Da bi zmanjšali izgube in optimirali proizvodnjo in transport stisnjenega zraka, je bil v okviru predstavljenega projekta uporabljen modelni pristop. Prispevek prikazuje dinamične modele za pomembnejše sestavine pnevmatičnega vezja. Trenutno se raziskujeta dva praktična primera uporabe teh dinamičnih modelov, in sicer: zaznavanje puščanja in optimizacija topologije pnevmatičnega vezja.

Modelno zasnovane simulacije delovanja pnevmatične infrastrukture omogočajo boljše razumevanje ter pomagajo določiti in ovrednotiti prihranjene potenciale. *Slika 1* prikazuje raziskovalna področja, ki so se izvajala v okviru projekta EnEffAH. Nekateri rezultati so predstavljeni v tem prispevku. Med raziskovalna področja spadajo: generiranje, distribucija in uporaba generaliziranega modelno zasnovanega optimizacijskega orodja.

Oblikovanje in dimenzioniranje posameznih pogonskih primerov je bilo izvedeno s pomočjo simulacijskih programov s podporo možnosti izbire velikosti in tipa sestavine, izračunom parametrov krmilnika in dopuščanjem natančnejše napovedi stroškov porabe energije. Simulacijski programi potrebujejo dinamične modele za dejanske sestavine, ki predstavljajo statično in dinamično obnašanje. Izvedenih je bilo veliko raziskav na področju konstruiranja oz. projektiranja vodnih oz. cevnih vezij z uporabo matematičnih postopkov.

Prispevek prikazuje postopek modeliranja sestavin vezja s stisnjenim zrakom, kot so kompresorji in tokovodniki. Nato podaja abstraktne modele sestavin pnevmatične mreže za detekcijo puščanja ter topološko optimizacijo za izboljšanje izkoristkov. S pomočjo simulacijskega programskega paketa Mathlab/Simulink je bil uporabljen koncept modelne določitve napak in izolacijskih tehnik (FDI). Uporabljeni sta bili dve glavni pnevmatični spre-

menljivki, to sta tlak in masni tok.

Model pnevmatičnega generatorja vsebuje enega ali več kompresorjev, enoto za vzdrževanje stanja zraka in centralno tlačno posodo. Glavni namen generatorja v omrežju stisnjenega zraka je neprekinjena dobava stisnjenega zraka in vzdrževanje konstantnega nivoja tlaka znotraj definiranega območja, ki naj bo čim ožje. Za raziskavo in določitev izkoristka posameznega kompresorja in celotnega generatorja stisnjenega zraka je potrebno razviti dinamične simulacijske modele. Posamezen računsko-simulacijski model kompresorja vsebuje termodinamične, električne in mehanske dele. Enačbi pod št. 1 podajata dinamična modela za izračun tlaka in temperature.

Matematično-simulacijski model tokovodnikov vključuje cevi različnih premerov in dolžin. Cevi se v simulacijskem modelu upoštevajo kot običajni pnevmatični upori (podobno kot ventili). *Slika 2* prikazuje poenostavljen model za pnevmatični prenosnik na osnovi C,b-vrednosti in dušene pretočne karakteristike. Predstavljeni enostavni simulacijski model prikazuje le eno od štirih karakteristik tokovodnikov, in sicer padec tlaka v odvisnosti od pretoka. Ostale tri karakteristike tokovodnikov: ''mrtvi'' volumen cevi, omejena hitrost tlačnih valov in refleksija tlačnih valov znotraj cevi so bile v tem simulacijskem modelu zanemarjene. Najenostavnejši način za postavitev kompleksnejših pnevmatičnih simulacijskih modelov je uporaba objektno orientiranih simulacijskih programov, kot npr. Dymola. *Slika 3* prikazuje pnevmatično funkcijsko shemo realnega preizkusnega pnevmatičnega vezja in njen abstraktni računski model (8 volumnov in 8 dušilk). Preizkuševališče vsebuje cevi s premeri ob 28 do 54 mm in dolžinami med 0,6 in 6 m. Implementacija progama Dymola je privedla do približno 2000 enačb, ki so bile samodejno poenostavljene. Zaradi poenostavitev dinamičnega modela so bili upoštevani le volumski in dušilni elementi.

Za kontrolo predstavljenih pnevmatičnih simulacijskih modelov so bile izvedene meritve na konkretnem industrijskem pnevmatičnem vezju. *Slika 4* prikazuje rezultate simulacij in meritev tlaka ter masnega pretoka med izvajanjem posameznih operacij s testirano industrijsko pnevmatično napravo. Levi graf zgoraj prikazuje rezultat simulacije (indeks s) in meritev (indeks m) za tlaka na mestu 4 in 7, desni graf pa prikazuje deviacijo med meritvami in simulacijo.

Metoda Kalmanovega filtra je uporabna za ugotavljanje puščanja pri pnevmatičnih vezjih z nelinearnim značajem. Metoda je zasnovana na dejstvu, da poznamo vhodne vrednosti in merimo nekatere oz. kombinacijo posameznih sistemskih vrednosti. *Slika 5* prikazuje rezultat postopka Kalmanovega filtra, namenjenega zaznavanju puščanja. Preostalo puščanje je prikazano na grafu spodaj. Za zaznavanje puščanja se uporabljajo tlačni senzorji. Za kvalitetno zaznavanje puščanja so poleg uporabljenih natančnih tlačnih senzorjev pomembna tudi mesta merjenja. Uporaba senzorjev za masni pretok je problematična z vidika visoke cene in težavnosti namestitve na ustrezno mesto v pnevmatičnem vezju.

Eden izmed pomembnejših ciljev projekta je bil tudi razvoj novega algoritma za optimizacijo topologije pnevmatičnega vezja z namenom, da se izboljša izkoristek. V tem delu so bili odkriti glavni vidiki: a) kje je potrebno namestiti cevi, da zagotovimo optimalno dobavo zraka do vseh porabnikov, b) kakšen je optimalni premer za vsako posamezno cev z vidika nizkih padcev tlaka pri pretakanju, c) kje namestiti dodatne tlačne posode, da premostimo problem različnih pretokov po ceveh in s tem naredimo pnevmatični sistem bolj robusten. Na sliki 6 je shematsko prikazana skica manjšega industrijskega pnevmatičnega vezja s 4 porabniki ''C'' in 8 možnimi cevnimi povezavami. Leva slika prikazuje originalno pnevmatično vezje, desna pa optimizirano vezje z lokacijo za dodatno tlačno posodo.

Ključne besede: vezje s stisnjenim zrakom, modeliranje sestavin, zaznavanje puščanja, optimizacija topologije, simulacije, merjenje tlakov

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