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HYBRID MODELING AND NONLINEAR DATA PROCESSING FOR BIOMEDICAL APPLICATIONS

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Abstract: The main purpose of this paper is to present application of hybrid (i.e. combined physical and *in silico*) modeling and nonlinear (fractal) biosignal analysis for improving quality of life through modeling and knowledge-based measurements in medicine.

Keywords: hybrid modeling, virtual instruments, nonlinear biosignal analysis.

1. INTRODUCTION

Modeling of circulatory system is important in biomedical engineering for testing and development of prosthetic devices and for planning of medical procedures as well as in education. Both numerical and physical models are used. Since different physical models have to be built for different applications such models are usually expensive while their accuracy and flexibility are rather poor. Numerical models are much cheaper, accurate and flexible, but their applicability is limited.

2. PURPOSE

To reduce costs and to shorten development time we have proposed so called *hybrid models* [1] - a combination of numerical and physical models. First, a numerical model is developed and then some of its parts are transformed into a physical model. To develop a hybrid model, any part of the numerical model can be replaced by a physical section (hydraulic, pneumatic, or electrical) and two interfaces (Fig. 1).

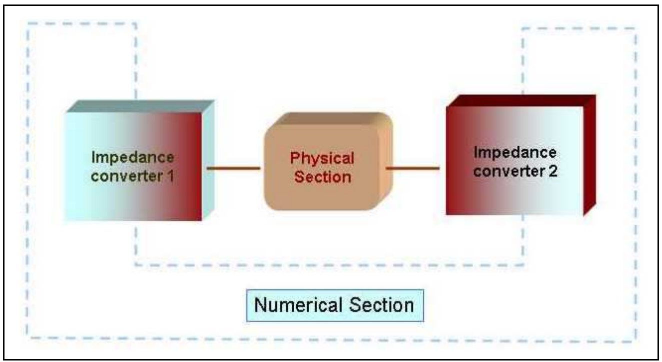

Fig. 1. The basic idea of hybrid model construction

The advantages of such solution are evident: the physical model is minimized and reduced to the barest essentials of the specific application; the numerical model that can be easily replaced or modified is to reproduce the remaining parts of the whole of the circulatory system. If the electro-hydraulic analogy is applied, the structure of the physical model can be either electrical or hydraulic. The critical issue, in both cases, is the interface. However, by using lumped parameter method the exchange between the numerical and the physical sections can be limited to one variable.

In our model the interface is based on impedance converter. It may be realized by a pure analog RLC circuitry or by a PC resolving a set of equations describing analog circuitry (Fig. 2).

3. METHODS

3.1. Modeling and measurement using electro-hydraulic impedance transformation

To design such an interface we have chosen the method of a proportional electro-hydraulic impedance transformation (Fig. 2). Electrically controlled flow sources are needed to build up impedance converters. The key element of the design is the electrically (voltage) controlled flow source, delivering flow q proportional to control voltage u_C independently of pressure drop Δp

$$q \sim u_{C1} \qquad (1)$$

Combining the flow source and the voltage source we obtain

$$q = k_q \cdot i \quad \text{and} \quad u = k_u \cdot \Delta p \qquad (2)$$

and as a result

$$Z_{in} = \Delta p / q = (1 / (k_q \cdot k_u)) \cdot (u / i) = 1 / (k_q \cdot k_u)) \cdot Z_e \qquad (3)$$

So electrical impedance Z_e connected to the electric terminals is proportionally converted into hydraulic impedance Z_{in} obtained on the hydraulic side of the converter.

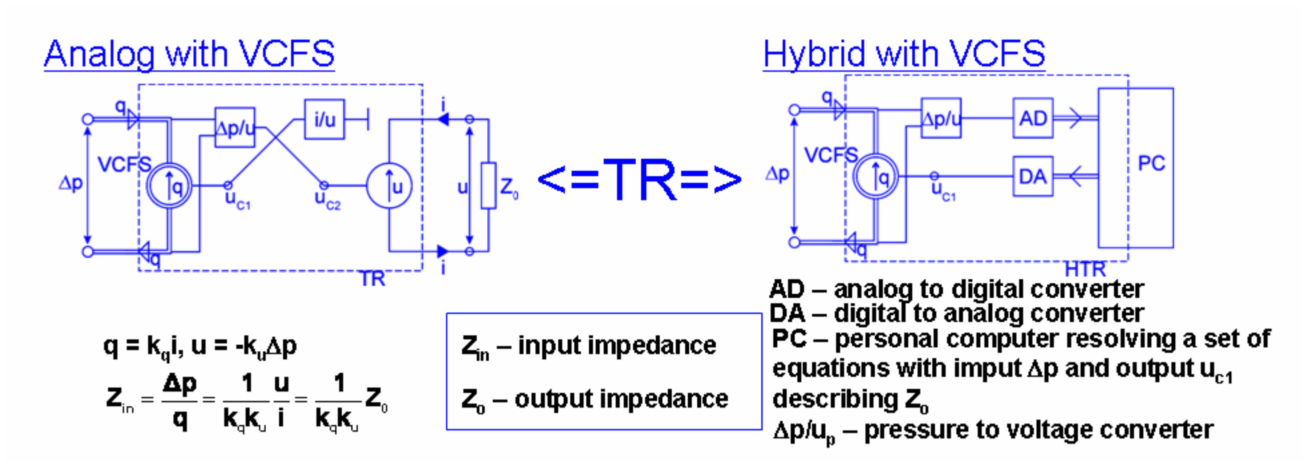

Fig. 2. Transformer - impedance electro-fluidic proportional converter .

3.2. An accuracy of the impedance transformation

Static and dynamic errors of impedance transformation are closely connected with an accuracy of the voltage controlled flow source VCFS (Fig. 2) which in our design is represented by a hydraulic gear pump (made by a workshop of the IBIB) driven by the MAXON DC-motor and controller. Static and dynamic characteristics of the VCFS are shown in Fig. 3. They are fairy linear and pressure independent as should be in the case of the nearly ideal flow source. A cut off frequency exceeds 500Hz what is sufficient to reproduce hydrodynamic phenomena of the blood circulation.

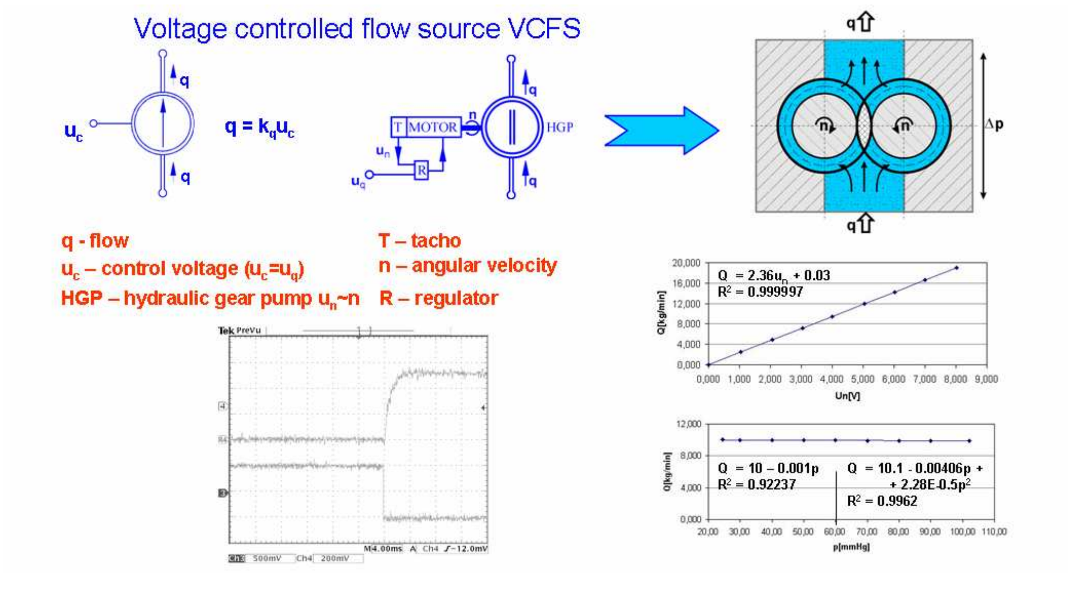

Fig. 3. Electrically controlled flow source FCFS

So FCFS may treated as a flow standard and no additional flow-meters are required in the hybrid model – it is enough to measure pressure to describe mechanical parameters of the model.

3.3. Modeling of nonlinearities

Thanks to the proportional impedance transformation any nonlinearity existing in the blood circulation system (e.g. a heart elastance, an aorta elastance) may be "transformed" to hydraulic terminals. This is a consequence of a consideration that this type of transformation doesn't influence a topology of the origin electrical (numerical) circuit i.e. electrical resistances, inductances, capacitances, voltage and current sources are proportionally transformed into hydraulic resistances, inertances, pressures, flows e.t.c. preserving the topology of the system. All time constants remain unchanged as the transformation invariants.

3.4. Modeling of long term "chaotic" Heart Rate (HR) variability

The presented hybrid model may be used to test new measurement methods e.g. fractal methods of a signal analysis. The human heart is an autonomic biological oscillator which frequency is influenced by a number of biofeedbacking mechanisms. HR is extracted as a result of an analysis of many signals accompanied by noises. HR variability may be easily introduced into the numerical section of the hybrid model then measured from pressure and flow courses in the hydraulic section by fractal analysis of these signals obtained from real physical measurements.

3.5. Knowledge-based biomeasurements - nonlinear signal transformation

Whereas in 'classical' methods one has always tried to work with linear parts of systems' characteristics introduction of PCs enabled to make use of nonlinear methods that are much more appropriate for biomedical applications [2]. Biosignals such as EEG, ECG etc. are nonlinear and nonstationary. Also it used to be a paradigm in Medicine, that constancy is the best for human health. New developments in Physics, such as Nonlinear Dynamics and Deterministic Chaos Theory, when applied to analysis of biosignals have shown that just the opposite is most probably true - *it is healthy to be chaotic*. For example, analysis of Heart Rate (HR) signals demonstrated, that heart rate becomes constant, heart rate variability (HRV) drastically diminishes, shortly before the patient death.

To the PC on Fig. 2 one may add another external loop that measures blood pressure of the patient and passes the signal to PC. PC calculates HR and HRV and extracts necessary information by calculating in real time one lumped parameter - *Higuchi's fractal dimension,* D_f (cf. [2]). Then calculated D_f is compared with knowledge-based D_f of HRV of a healthy person and the signal passed to the physical sections is controlled in such a way that the output pressure changes in time in an appropriate way.

Similar device may be used for modeling of respiratory system. If the outer loop is equipped with a monitor that enables to the patient observation of the calculated D_f and/or other characteristics of the physiological state, such a device may be used for *biofeedback.*

4. RESULTS

We have constructed in our Lab impedance electro-fluidic proportional converter. In particular, we built up a Voltage Controlled Flow Source (VCFS) - a special gear pump that shows excellent linearity and a high output resistance.

The general method presented above may be applied to build up any part of the hybrid physical-numerical model of circulatory system. The final shape of the model depends on the application. For example, we investigated application of an intraaortic balloon pump.

5. CONCLUSIONS

The presented method reveals opportunities not earlier available like modeling complex electrohydraulic phenomena including blood flow dynamic simultaneously taking into account heart rate variability.

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