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# ARTICULATION-RELATED FEATURES IN THE PIPE ORGAN SOUND

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Investigations in the domain of sound growth in organ pipes resulted in describing some of the articulation-related features. An equivalent electrical circuit of an organ action was created basing on computer modeling techniques. The response characteristics of the circuit were obtained numerically and are discussed. The concept of an organ action governing a digitally controlled valve is proposed and examined. A comparison between the response characteristics of the equivalent electrical circuit, the tonal characteristics of an exemplary pipe and characteristics obtained through the analytic modeling of pipes is presented and discussed. Numerical simulations are found to be in good conformity with experimental results. Among the latest electronic hardware achievements, the fuzzy logic-based knowledge acquisition and control system seems to be a capable tool for solving the problem of control of the electromagnetic valve of the organ pipe. A model of a pipe organ with a fuzzy logic-based control system was designed, constructed and investigated. Results of studies and experiments in the domain of pipe organ valve control are presented in the paper.

## 1. Introduction

Computerizing classical pipe organs opens a new domain of interests, in which modern technology meets the traditional way of playing such instruments. The application of a microprocessor system to an organ may significantly improve many of the control and display functions of the console. Computer control of the pipe organ also enables a new approach to the problem of existing musical articulation limitations in a pipe instrument with an electromagnetic action. This kind of pipe organ control is characterized by the promptness in the pipe response, as the air flow cannot be controlled otherwise than by the rapid opening and equally fast closing of the valve. In the opinion of organists, this deprives them of the possibility to interpret music according to their wishes.

The differences between particular organ instruments in terms of control system design directly affect their performance evaluation as expressed by musicians and listeners. This type of research was carried out during the 1950's and 1960's. However, the research methods applied then were scarcely precise. New interest in the analysis of pipe organ sound derives from the fact that many physical features formed during instrument production are not sufficiently recognized to form a basis for the design of contemporary pipe organ instruments. The theoretical studies of organ pipes, both the classical ones of Lord Rayleigh and Brown and later those of POWELL [23], BENADE [1] and COLTMAN [5], do not present a uniform opinion on the dynamic behavior of wind instruments. That is why a fully adequate pipe simulation model was not as yet elaborated. Various techniques have been applied in order to extract parameters relevant to the physics of an organ pipe. Some of these date from at least the early 1950's, with papers by RICHARDSON [26] and RAKOWSKI and RICHARDSON [25] being among the earliest references. Another approach based on the work of CADDY and POLLARD [3] considers only time domain analysis of attack transients for a tested pipe organ. Early work of FLETCHER [9] was based on calculations of both steady state oscillations of the organ pipe and overblown regimes in nonlinear interaction with excitation. As pointed out by KEELER [12], the evidence of overblown regimes in initial transients cannot be neglected. During the build-up of the sound, the sound pressure is changing significantly. An efficient method of modeling the pipe sound, both analytically and numerically, was originally described by FLETCHER [10] and has been used for this purpose by SCHUMACHER [27], NOLLE and FINCH [20] and re-examined by KOSTEK and CZYŻEWSKI [14]. Schumacher based his study on Fletcher's model in terms of a nonlinear equation of the Hammerstein type and obtained the oscillating waveform to an arbitrary harmonic number. Nolle and Finch described both experimental study and numerical simulations of flue pipe starting transients, based on the elaborated model. They reported the relation between the speed of pressing the key and the overshoot which appears in the sound attack in organs having mechanical tracker action. They observed the percussive character of an attack in two cases, namely when the burst occurs (a second or third harmonic dominates the starting transient) or when the energy of higher harmonics is bigger than that of the fundamental. Nolle and Finch observed these phenomena in their experimental tests. They also apply test results to the numerical simulations, and as a result some initial parameters were based on observations made during their experiments [20]. Rakowski and Richardson and also Lottermoser mentioned another effect, which may be referred to as the precursor, preceding the attack itself. However, this happens when the air is just starting to be admitted into the pipe, thus from the musical viewpoint the resulted sound does not last long enough to have discernible pitch [18, 25].

Reviewing the most common organ action types, one can find significant mechanism features which cause differences in the sound produced. Among the organ actions, mechanical, pneumatic, electrical and mixed ones may be identified [29]. The first type provides the sound most preferred both by organists and by listeners. The pneumatic or electropneumatic control of the organ are only found in organs built previously. On the other hand, the electrical action is usually chosen by modern organ builders because of the possibility of separating the control system from the rank of pipes. Time delay caused by the operation of the organ mechanism might be one of the criteria of the quality of an organ action [15, 22] and the resulting sound. Up to some value, time delays in the operation of an instrument may be tolerable, though a synchronous response to the performance of the organist is desirable. In the case of a mechanical action, delays caused by this system are mainly that of opening the pallet in order to build up the pressure in a key chamber. The direct electrical control due to the lack of intermediate air or wood passages does not affect the time of opening the pallet. Nevertheless, the initial time delay is only one of the factors characteristic of the differences in a pipe sound response. It is possible to determine another factor associated with the articulation features having an influence on the quality of the pipe sound, namely the way in which the transient attack is building up [12, 14]. The measurement procedures which allow the extraction of parameters for the above mentioned investigations will be reviewed in the next paragraph.

The aim of the presented research is three-fold. First of all, the aim is to examine the operation mechanisms in order to build up an equivalent electrical circuit of a mechanical organ action. The proposed and examined model is later modified using a multi-step source in order to discuss the concept of a digitally controlled organ action. Secondly, a comparison is presented between the response characteristics of the pipe-equivalent electrical networks, the data taken from the experimental investigations, and characteristics obtained from the analytic model of the pipe based on Fletcher's analytic model [10]. The third aim of the present investigations concerns the possibility of equipping an organ tracker action with a fuzzy-logic-based control system. A model of a pipe organ using a fuzzy-logic-based control system was designed, constructed, and investigated. These investigations were mainly confined to the sound features of the starting transient in order to meet quality requirements for the pipe organ sound in the domain of musical articulation.

## 2. Experimental background of the organ pipe sound articulation

### *2.1. Time delays*

For the purpose of investigating and comparing various tone qualities of the organ sound, a measurement program was established. It should be remembered that the change of velocity of opening the mechanical pallet is the result of the force impressed upon the key. Consequently, the velocity of the key motion has been selected as a relevant parameter associated with the articulation features in organ music. That choice was also confirmed in previous tests [16]. Subsequently, it was noticed that the velocity of the key motion can be replaced by a quantity being more convenient to measure, namely by the time of key depression from its upper to its lower position, the latter being the state of full depression.

Resulting from the above assumptions, the data for analyses was acquired through the simultaneous recording of the time of key depression and the resulting sound produced by the pipe. The lay-out of such a measurement method is presented in Fig. 1. Sounds were recorded in the St. Nicholas Basilica in Gdańsk, having a mechanically controlled organ, and in the Oliva Cathedral, where the organ is controlled with both electropneumatic and direct electrical pallet control. A microphone was placed close to the selected pipe, in the direct field, in order to limit the influence of church acoustics. The position of the key motion was registered through a pair of piezoelectric film sensors installed at

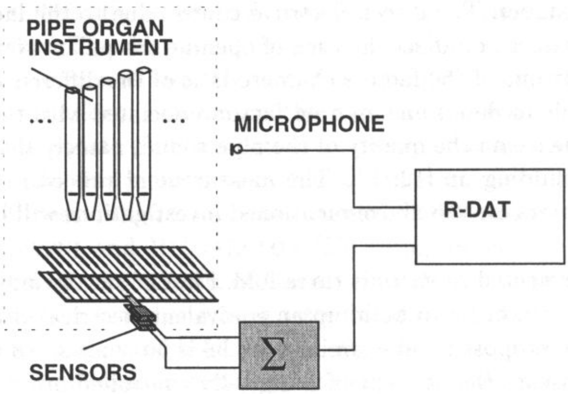



Fig. 1. Lay-out of the signal recording system.

the depressed key (Fig. 2 a, b) which corresponded to the pipe being recorded. Special construction of the sensors allows for their activation only when the plate is moving in one direction, which in this case is from the upper position to the lower one. Therefore, the sensor placed above the key (Fig. 2 a) generates an impulse in the initial phase of pressing the key, whereas the sensor placed under the key (Fig. 2 b) does it in the final phase. The time between the activated impulses can be taken as approximately the time of pressing the key. The sensors are constructed with the use of piezoelectric foils adhered with thin band layers [21]. Electrodes are applied to the polarized film. The sensors have a built in electronic commutator which enables impulse generation at the moment of pressing the piezoelectric film. The structure of electrical connections in this commutator is shown in Fig. 2 c. The assigned letters, namely: A, B, C, D, E in the schema, correspond to points where electric current was measured. Exemplary current characteristics are shown in Fig. 2 d. During the recording, impulses from the sensors were recorded on one of the tape recorder channels which later allowed for identifying the time of pressing the key.

Organs were tested in two different ways, with fast and slow depression of the key according to the demands of musical articulation. The recorded material was subjected to a detailed analysis in order to study the relation between the velocity of the key motion and the resulting articulation features. This made it possible to find the values of the time interval corresponding to the duration of the key motion. This kind of analysis is shown in Fig. 3. Values of $\Delta t$ in Fig. 3 correspond to key depression times. Additionally, the results of the analyses of key motion are shown in Table 1. The values of time intervals for different key velocities in Tab. 1 are divided into three ranges in the case of the mechanical action. Consequently, as is seen from Tab. 1, the initial delay corresponds very closely to the values quoted in the literature [15, 22] and the mechanism operation of the wood tracker connections may be neglected, both for a slow and fast depressing of the key. On the other hand, there is practically no correlation between the corresponding values of the way a key is depressed when performing on an organ using either an electropneumatic or an electrical action. In the case of the electropneumatic

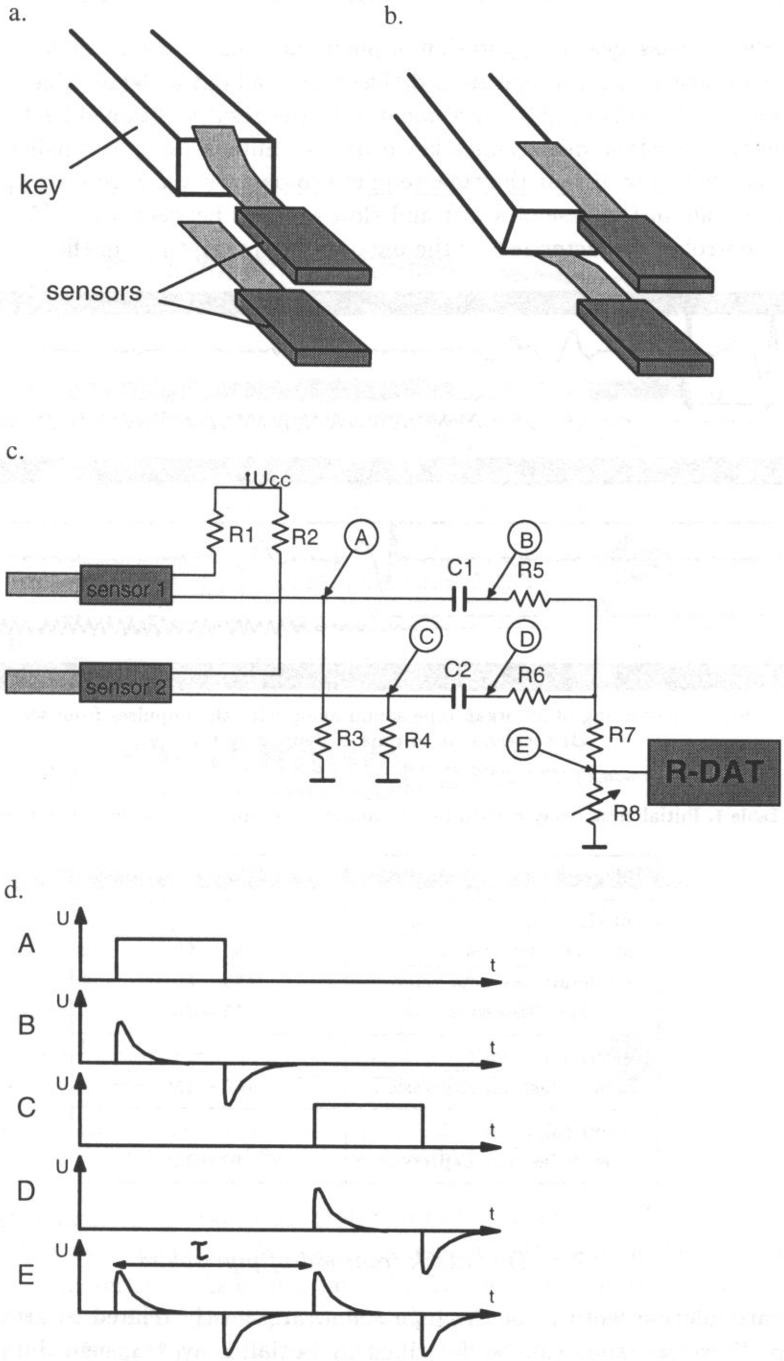



Fig. 2. Registering the time of pressing the key with the use of piezoelectric sensors, a) the key in the resting position, b) the key pressed, c) block diagram of the electronic commutator, d) exemplary current characteristics measured in the assigned measurement points (see Fig. 2 c).

system, the air passages and operation of pneumatic motors cause such delays that the time of key movement may be neglected. The increased initial delay value in comparison to the other systems is in good agreement with the results obtained by POLLARD [22]. In the electrical system, depressing a key evokes an impulse to open a pallet without any delay. It has been noted that the time required to depress a key from its upper position to the lower one in the case of a fast and slow touch is between 10 to 15 ms. This type of organ control is characterized by the outstanding promptness in the pipe response.

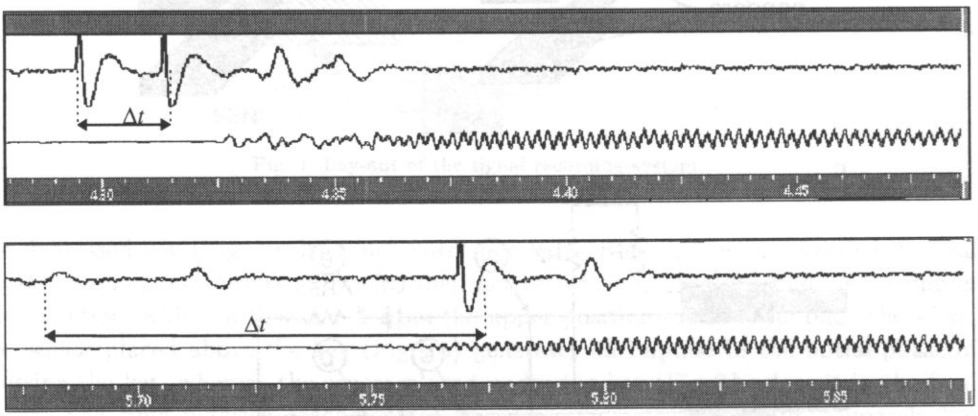



Fig. 3. Recording of an organ pipe sound along with the impulses from sensors ($\Delta t$ corresponds to time of depressing the key).

**Table 1.** Initial time delay caused by key motion and operation of the control system.

| Type of pipe organ action | Initial time delay [ms] |
|---|---|
| mechanical: | |
| slow key depression | 50 – 90 |
| moderate key depression | 30 – 50 |
| fast key depression | 15 – 30 |
| electropneumatic: | |
| slow & fast key depression | 100 – 150 |
| electrical: | |
| slow & fast key depression | 10 – 15 |

### *2.2. The attack transient of pipe sound*

The articulation features of the pipe sound are mostly related to attack transient building. Therefore, they can be described by initial delay, transient duration and by growth of subsequent harmonics. Figure 4 illustrates the signal envelopes of the note $a$ (110 Hz) of the Principal 8′ in the cases of quickly and slowly depressing the key. Comparison of the two characteristics clearly shows the differences occurring during the stage of growth of the sound. Thus, it is expected that the differences in musical articulation are determined by the attack transient. Subsequent listening to the extracted transients shows that the pitch of the initial transient is an octave above the pitch of the fundamental.

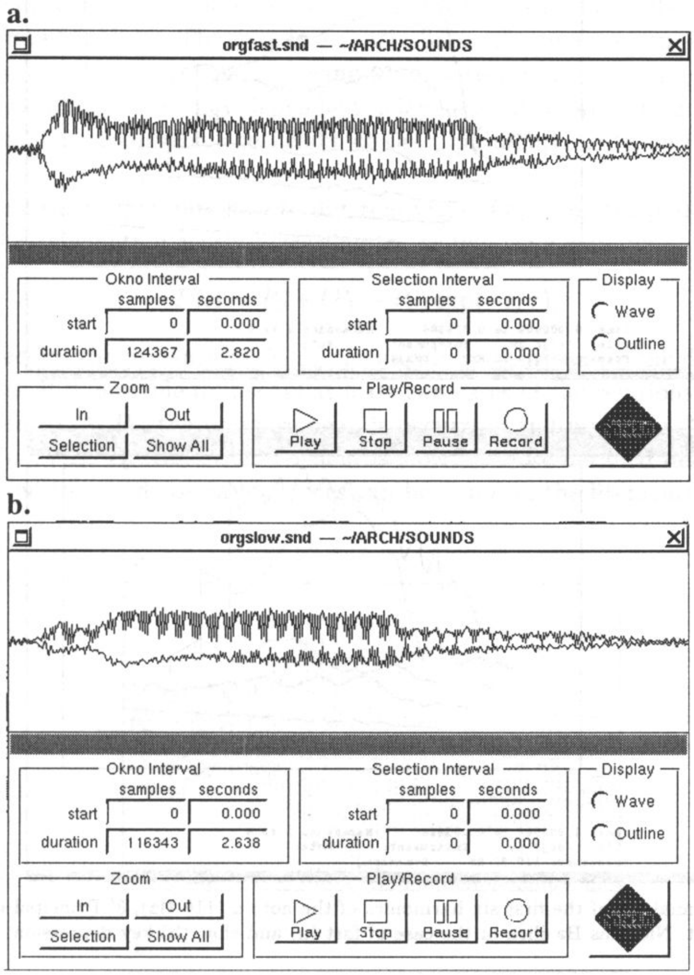
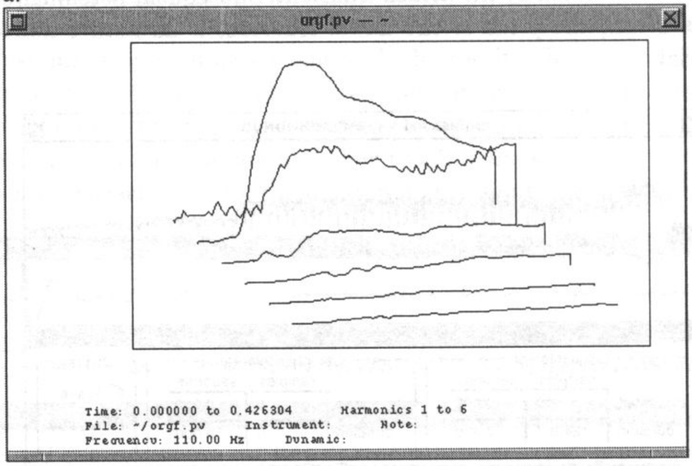



Fig. 4. Signal envelopes, note $a$ (110 Hz), 8′ Principal of the organ of St. Nicholas Basilica in the case of fast (a) and slow (b) key depression.

The spectral analysis of transients is plotted in Fig. 5. The attack transient is dominated by the first two harmonics. A delay with respect to the way the key is depressed is visible in the characteristics. As is seen from Fig. 5 a, there is an initial rise in the second harmonic in the case of fast key depression, and the delay of the signal transient differs in character, being longer for the fundamental. It was noted that during the period of the overblown regime, the produced sound is an octave higher than the normal pitch. In the case of a slow attack (Fig. 5 b), the rise of the transient is also slow and the fundamental builds up very smoothly, rising more quickly and at the same time more strongly than the other components.

a.




b.

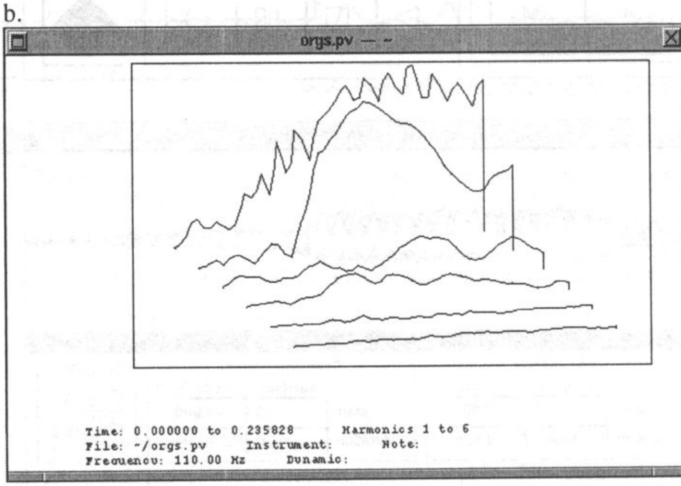



Fig. 5. Spectral analysis of the first six harmonics of the note $a$ (110 Hz), 8′ Principal of the organ of St. Nicholas Basilica in the case of fast (a) and slow (b) key depression.

To verify the above stated observations, sound simulations were performed based on the physical model of pipe organs. One of the methods belonging to the category of physical modeling is "digital waveguide" synthesis [6, 7, 28, 30, 31]. In this method, the wave equation is first solved in a general way to obtain the traveling waves in the instrument body that are then simulated in the waveguide model [6, 7, 28]. What is important, the initial stage of sound rise, critical to the subjective assessment of the naturalness of the organ sound produced by pipes, was modeled with results showing that sounds produced in models in which the air flow conditions were differentiated better resemble the natural sound [7].

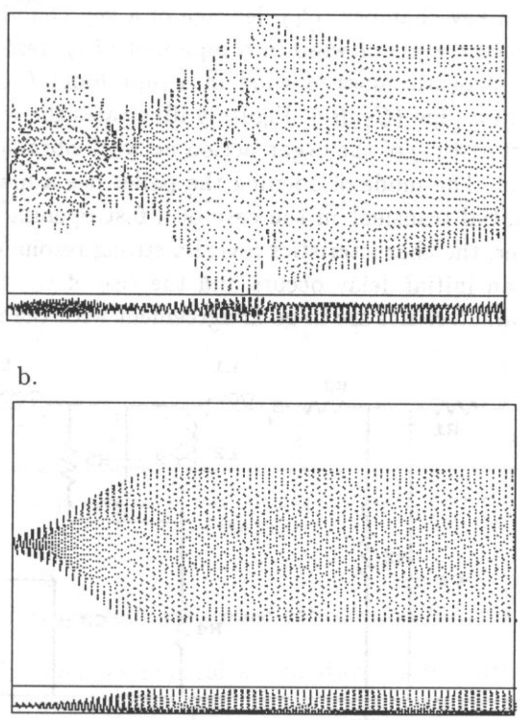
Another approach to physical modeling is focused on the mathematical model of the behavior of the pipe when treated as a system. A detailed analytic description and modeling of transients in the speech of organ flue pipes has been treated by FLETCHER [10] and reviewed intensively in the literature [7, 11, 14, 20]. Several models of organ flue pipe have been developed during recent years (e.g. [4, 5, 8, 19, 32, 33]). However, the existing general concept of the pipe system assumes at least two sub-systems and the interaction between them. The first is a nearly linear resonant system of the pipe and the second is a nonlinear system of blowing wind, with the assumption of its interaction with the pipe. Also, a frequency-dependent delay element, representing the time for jet deflection waves to transverse the height of the pipe mouth, is to be included in this model.

By relating the air pressure flow to different ways of opening the pallet, it is possible to express the articulation aspect according to the following equation:

$$P(t) = P_0 + (P_1 - P_0)\exp(-t/\tau), \tag{2.1}$$

where $P_1$ specifies the pressure peak, $P_0$ the steady pressure and $\tau$ the decay time from the peak level. It is possible to discuss at least two cases of the relationship between $P_1$ and $P_0$. When $P_1 \gg P_0$, the pressure peak is occurring and may be referred to as fast attack. When $P_1 \ll P_0$, then the transient is slow. A more detailed description of the features related to sound rise in flue pipes can be found in the literature [7, 10, 16].

a.



b.

Fig. 6. Graphical presentations of pipe sound simulations, a) in the case of fast attack, b) in the case of slow attack.

The numerical model implemented on the UNIX workstation using the *Mathematica* system was verified by multiple listening examinations of the model output sounds obtained from real-time simulation of the pipe speech response (see Fig. 6). Listening to the signal patterns from the computer simulations makes it possible to state that if the air pressure is activated slowly, the resulting sound is in agreement with the fundamental pitch. If the air flow is fast, then the pitch of the initial transient seems to be one octave higher than that of the steady sound, confirming previously obtained results. Moreover, the impression of the pitch being of the proper tune occurs only after the delay of about 100 ms.

## 3. Pipe organ action modeling

### *3.1. Equivalent electrical circuit of an organ action*

A general approach to the design of an equivalent electrical circuit of an organ action was made by CADDY and POLLARD [3]. However, the description of the resulting circuit was very simplified, thus requiring completion and then verification. Therefore, a revised and completed equivalent electrical circuit was built up in order to model the operation of the organ action. In Fig. 7, the organ action is represented by the following parameters: pressure of blower driving a circuit ($V_1$), internal resistance of blower ($R_1$), capacitance of a key chamber ($C_1$), leakage of a key chamber ($R_2$), resistance of a pipe foot ($R_3$), acoustic mass of wind in a pipe foot ($L_1$), resonant system of a pipe foot ($L_2, C_2, R_5, R_4$), acoustic mass of wind in a pipe foot ($L_3, R_6$), and capacitance and leakage of wind in a pipe ($C_3, R_7$). Figure 8 illustrates the response characteristics (the indicated characteristics) of the organ action network obtained using the computer modeling analysis tool. The mode of opening the pallet has a marked effect on the initial transient. The initial transient in the case of a fast opening of the pallet is sharp and smooth. Moreover, the characteristics reveal a strong resonance effect. For slow depression of the key, an initial delay occurs and the rise of the transient is slow. It is notable that both characteristics are in good agreement with the results obtained in the

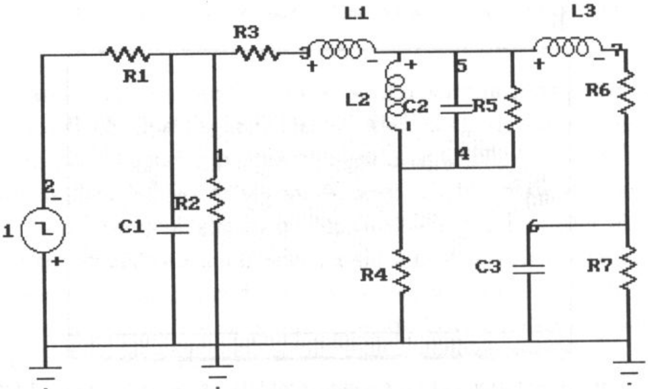



Fig. 7. Equivalent electric network of an organ action.

experimental procedure described previously. In order to examine the influence of the parameters on the response characteristics, the value of the capacitor $C_1$ was changed. An increase in the value of the capacitor $C_1$, representing the volume of the key chamber, eliminates the resonance effect and the response curve becomes flat. This relation between the volume of the key chamber and the resulting pipe response is confirmed both by theory [18] and in practice.

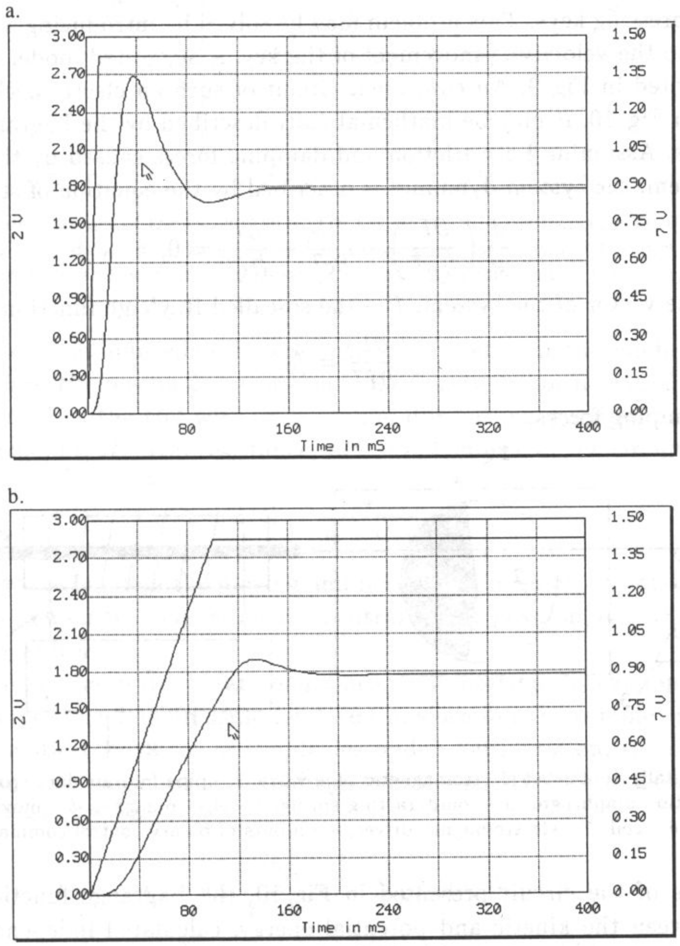



**Fig. 8. Initial transient, a) in the case of fast opening the pallet, b) in the case of slow opening of the pallet.**

### *3.2. Digitally controlled articulation features*

A mechanical action enables musical articulation by the direct wood tracker connections between a key and a pallet [29]. In the case of an electrical organ action, in whatever way a key is depressed, the electromagnet reacts equally quickly. Digital control of an organ makes possible a system which consists of an electronically controlled articulation action but which still ensures the quality of sound similar to that obtained from organs having mechanical actions. Such digital control of an organ imposes quantization of the key velocity or another related parameter easier to measure, namely that of key depression time from its upper to its depressed position.

*3.2.1. General characteristics of a valve model.* In order to control the articulation features in a pipe organ, it is necessary to relate the way of opening the pipe valves to the way of depressing keys. This problem may be solved by introducing a stepping valve which reacts to the velocity of movement of the key. A suggested model of that kind of valve is presented in Fig. 9. An equivalent circuit of such an electromechanical system is presented in Fig. 10. It may be mathematically described by the Lagrange function of state variables. Assuming both friction and damping forces caused by the operation of the given system, the system dynamics is described by the equation of state [24]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}^T}\right) - \frac{\partial L}{\partial q^T} - \frac{\partial F}{\partial \dot{q}^T} = 0, \tag{3.1}$$

where $q$ – state vector of the system, $F$ – the so-called Rayleigh function defined as:

$$\frac{\partial F}{\partial \dot{q}^T} = f_0, \tag{3.2}$$

where $f_0$ – damping forces.

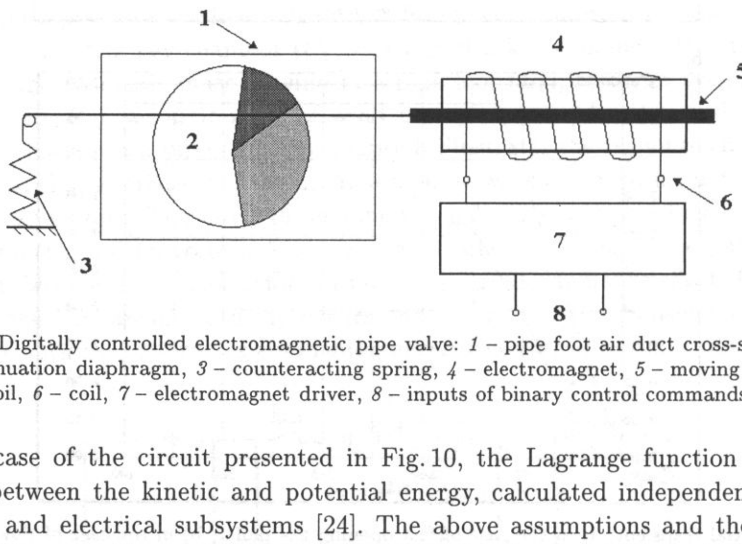



Fig. 9. Digitally controlled electromagnetic pipe valve: *1* – pipe foot air duct cross-section, *2* – attenuation diaphragm, *3* – counteracting spring, *4* – electromagnet, *5* – moving magnet coil, *6* – coil, *7* – electromagnet driver, *8* – inputs of binary control commands.

In the case of the circuit presented in Fig. 10, the Lagrange function equals the difference between the kinetic and potential energy, calculated independently for the mechanical and electrical subsystems [24]. The above assumptions and the condition that potential energy $U_0$ equals 0 for the electrical subsystem result in a set of differential equations describing the dynamic performance of the system. The first equation (3.3) describes the motion of the moving core, and the second (3.4) is related to the current induced in the windings:

$$M\ddot{l}(t) + B\dot{l}(t) + K[l(t) - l_0] + \frac{A}{2[d_0 + l(t)]^2} i^2(t) = 0, \tag{3.3}$$

$$\frac{A}{d_0 + l(t)} \dot{i}(t) + Ri(T) - \frac{A}{[d_0 + l(t)]^2} i(t)\,\dot{l}(t) = u(t), \tag{3.4}$$

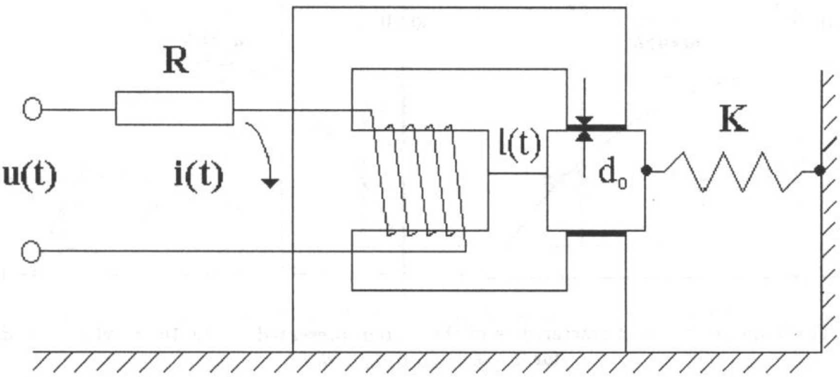



Fig. 10. Equivalent model of the system shown in Fig. 9: $R$ – coil resistance, $u(t)$, $i(t)$ – voltage and current in the windings, $d_0$ – thickness of the antimagnetic separator, $l(t)$ – distance between the moving and permanent magnet, $K$ – elasticity coefficient of the spring.

where $i(t)\,\dot{q}(t)$ – current induced in the windings, $u(t)$ – voltage in the windings, $M$ – mass of the moving core, $B$ – mechanical resistance, $K$ – elasticity coefficient of the spring, $A$ – coefficient related to the coil wire cross-section dimensions, number of windings and the magnetic constant, $R$ – coil resistance, $L(t)$ – inductance of the circuit:

$$L(t) = \frac{A}{d_0 + l(t)}, \tag{3.5}$$

where $l(t)$ – distance between the moving and permanent magnet, $l_0$ – distance between the moving and permanent magnet for the neutral spring position, $d_0$ – thickness of the antimagnetic separator.

On the basis of the system state equations, it is possible to examine the system performance in the time domain using Laplace transforms or the complex plane. Taking into account the static behavior of the device under consideration, the characteristics $U = f(L)$, relating a given value of the voltage $U$ in the steady-state to a certain position of the movable core ($L$), becomes:

$$U = \pm R\sqrt{\frac{2K}{A}(l_0 - L)(d_0 + L)^2}\,. \tag{3.6}$$

Assuming $l_0 < d_0/2$ for $0 < L < l_0$ the characteristic $U = f(L)$ may have the form shown in Fig. 11 a. On the other hand, when $l_0 > d_0/2$, then the expression $U = f(L)$ has its maximum, therefore the characteristics is indeterminate (Fig. 11 b).

The mathematical description of physical artefacts occurring in the presented model result in a fairly complicated form. Although it is possible to devise the control structure of such a model, it is not enough to operate the system based on the adopted formula. However, taking into consideration a simplified description of the system it is possible to derive some practical rules governing the relationship between the speed of diaphragm motion and the supplying current. These principles may be intuitively explained on the basis of Fig. 9. Analysis of Fig. 9 shows that the electromagnet opening the attenuation

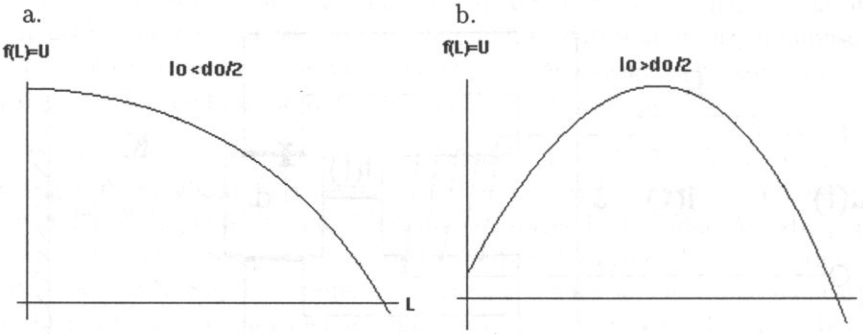



Fig. 11. Shapes of static characteristics of the system presented in Fig. 10, a) when $l_0 < d_0/2$ for $0 < L < l_0$, b) $l_0 > d_0/2$.

diaphragm must overcome the resistance of the counteracting spring. This may occur, provided the electromagnet coil is fed with sufficient electrical power. Providing that the power is limited, the valve remains in a partially-opened position. Consequently, the value of the current in the coil circuit is decisive to the position of the air flow diaphragm. Thus, the dynamic which governs the regulation of the coil current may allow for the control of valve diaphragm motion according to the way of the key is depressed.

Obviously, digital control of an organ imposes the discretization of the key velocity parameter and, consequently, the coil current value. The system should generate signals that for a given control structure, will set the system into the desired state within a minimum time and with minimum energy consumption. That problem is directly related to the organization of data transmission from the console to the organ wind chests. Nevertheless, using a fiber-optic link for fast data transmission, that matter becomes of secondary importance. On the contrary, the influence of the number of discretization levels on the cost of the electromagnetic valve should not be neglected. Since several hundreds of pipe electromagnets are used in typical organs, the application of digital-to-analog converters in the coil drivers cannot be considered because this kind of electrical drive would be impractical and costly. Hence, the coil current might be switched on in four steps, namely 0, 1/2, 2/3, 1/1 of its full value. However, as it will be shown in Sec. 4, by using fuzzy control technology this problem can be solved differently and in a less expensive way.

*3.2.2. Validation of the model.* In the preceding paragraph, a simple organ action system was considered (see Fig. 7). It is also possible to create an equivalent electrical circuit analogous to the mechanical organ action network with regard to articulation features. The model consists of a modified source of blowing wind, namely a multi-step source reacting to the way of depressing a key. The model is shown in Fig. 12. All the symbols are the same as described in Sec. 3.1. The only modification made was to replace $V_1$ and $R_1$ by the consecutive parameters $V_{11}$, $V_{22}$, $V_{33}$ and $R_{11}$, $R_{12}$, $R_{13}$, representing the multi-source and their internal resistances. The four-step source simulates the consecutive phases of opening the pallet, namely closed, opened slightly, opened to 2/3 of the full flow of wind, opened to the full flow of wind.

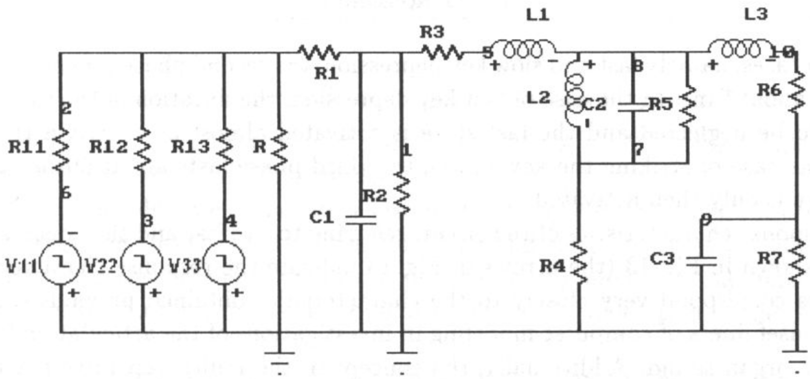



Fig. 12. Equivalent electric network of an organ action with a modified source.

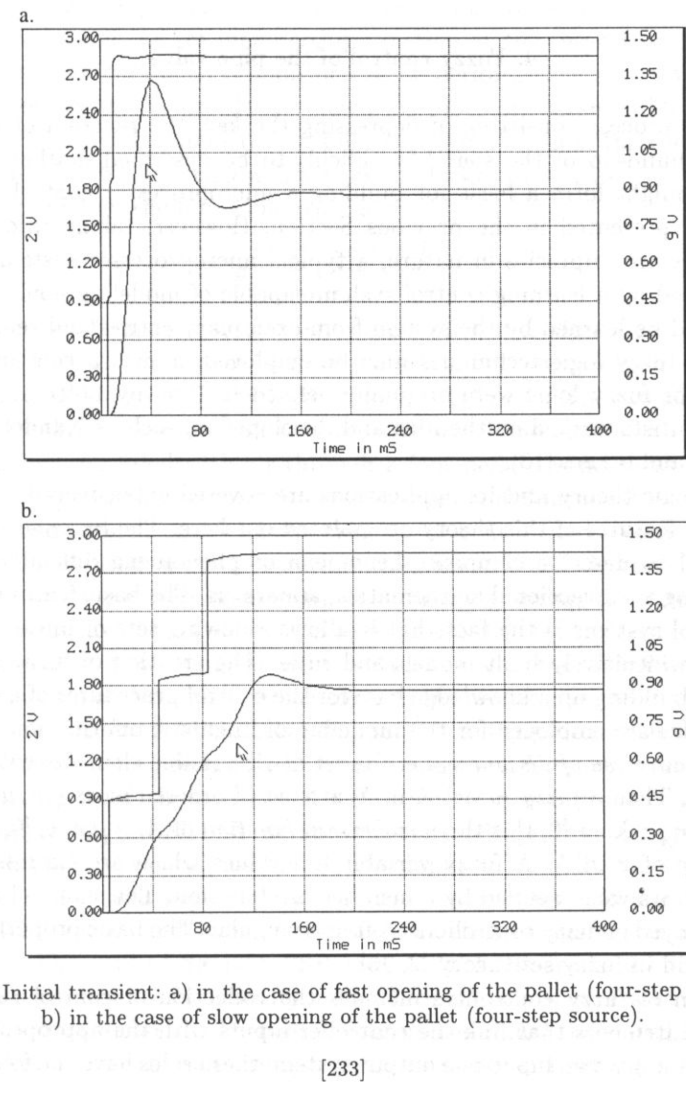



Fig. 13. Initial transient: a) in the case of fast opening of the pallet (four-step source), b) in the case of slow opening of the pallet (four-step source).

In both cases, namely fast and slow key depression, the second phase (opened slightly) takes only about 5 ms. In the case of fast key depression, the duration of the third phase is nearly to be neglected and the last state is activated almost at once. On the other hand, in the case of striking the key slowly, the third phase lasts about 50 ms, and the fourth state is only then activated.

The response characteristics of the circuit referring to the fast and slow depression of a key are shown in Fig. 13 (the arrows in Fig. 13 indicate the response characteristics). The results correspond very closely to the characteristics obtained previously, so this proves the usefulness of computer modeling in investigations of the articulation features in the pipe organ sound. Additionally, the concept of the multi-step valve reacting to the way a key is depressed has been verified using this technique.

## 4. Fuzzy control of the pipe valve

The whole process consisting of depressing the key, the reaction of the valve and the resulting build-up of the sound is difficult to be described mathematically. Such a description might form a basis for building a microprocessor control system of the organ, as was presented in the previous Section. However, taking into account that these processes are imprecise in nature, a typical microprocessor system for an organ may be replaced by a learning control system capable of modeling nonlinearities. Such modeling could be learned by the system from exemplary entries and related decisions. Consequently, fuzzy logic techniques may be employed in such a control system. The assumptions for fuzzy logic were originally defined in 1965 by Lofti A. Zadeh. Later, numerous scientists worked on the idea and developed it, such as Kandel, Lee, Sugeno, Kosko, Yager and others [13].

As fuzzy logic theory and its applications are covered extensively in the literature, only the main features of this theory are pointed out here. The fuzzy set theory results from the need to describe complex phenomena or phenomena difficult to define and determine using a conventional mathematical apparatus. The basic feature of fuzzy logic used in control systems is the fact that it allows following sets of linear and nonlinear functions with intuitively built models and rules. The creation of fuzzy rules must be proceeded by building up a knowledge base for the control procedures of a system. Fuzzy *IF–THEN* rules are employed for the modeling of linguistic information. Suppose that $X = \{x\}$ is a *universe of discourse*, i.e. the set of all possible elements with respect to a fuzzy concept. Then a *fuzzy subset* $A$ in $X$ is a set of ordered pairs $\{(x, \mu_A(x))\}$, where $\{x\} \in X$ and $\mu_A : X \to [0,1]$ is the *membership function* of $A$; $\mu_A(x) \in [0,1]$ is the *grade of membership* of $x$ in A. A fuzzy variable has values which are expressed in natural language, with its value defined by a membership function. The shape of a membership function employed in fuzzy controllers is often triangular. The basic properties of Boolean theory are valid in fuzzy set theory [2, 13].

The design of fuzzy controllers includes the collection of control rules consisting of linguistic statements that link the controller inputs with the appropriate, respective outputs. Assuming a two input-one output system, these rules have the following general structure:

$$R^{(r)}: \quad \text{if } x \text{ is } A_i^{(r)} \text{ and } y \text{ is } B_i^{(r)} \text{ then } z \text{ is } U_i^{(r)}, \tag{4.1}$$

where $r = 1, 2, 3, ..., n$; $x$, $y$, $u$ – fuzzy variables, $A_i^{(r)}$, $B_i^{(r)}$, $U_i^{(r)}$ – fuzzy subsets in the universe of discourses $X$, $Y$, $Z$, respectively.

For the given rule base of a control system, the fuzzy controller determines the rules to be fired for the specific input signal condition and then computes the effective control action. Applying inference operators *sup-min* or *sup-prod* (e.g. *supreme-minimum, supreme-product*) to the composition operation results in generation of the control output [2].

In fuzzy set terminology, another notion is defined, namely the "*fuzzification*" operation. It can be performed by considering the crispy input values as "singletons" (fuzzy sets that have membership value of 1 for a given input value and 0 at other points) and taking the values of the set membership function at the respective data value [2]. Additionally, the "*defuzzification*" operation can be performed by a number of methods of which center-of-gravity (centroid) and height methods are common [2]. The centroid defuzzification method determines the output crisp value $U_0$ from the center of gravity of the output membership function weighted by its height $\mu(U)$ (*degree of membership*) and may be described by the following expression:

$$U_0 = \frac{\int U \cdot \mu(U)\, dU}{\int \mu(U)\, dU}. \tag{4.2}$$

For the purpose of this research, a physical model of a pipe organ was designed and constructed [17]. It consists of two elements: a model of an organ tracker action and a control system based on fuzzy logic technique (Fig. 14). The model of the organ was made from oak, and consists of: bellows with a volume of $0.06\,\mathrm{m}^3$, covered with leather (the bellows are filled with air through a foot pedal); wind chest sized $0.4\,\mathrm{m} \times 0.3\,\mathrm{m} \times 0.2\,\mathrm{m}$; two organ pipes (Principal 8′ – tin pipe, and Bourdon 8′ – wooden pipe); and a tracker action which enables both mechanical control and electrical activation. Three electromagnets used in this control system are combined electrically to one key. The valve is driven by electromagnets with counteracting spring. Electric activation is obtained through the use of a set of electromagnets controlled by a system constructed on the basis of fuzzy logic. Activating the electromagnets causes the air inflow to a selected pipe. A block diagram of the system which controls the electromagnets of the organ pipe valves is shown in Fig. 15. Additionally, the system configuration is shown in Fig. 16. The following components are included: dynamic keyboard, sensitive to the velocity of key motion, connected through a MIDI interface to the computer; PC computer with software operating the FUZZY microprocessor card; FUZZY microprocessor card and the MIDI interface card installed in a PC computer; specially constructed control display of key number and key velocity; buffer of information exchange between the MIDI and FUZZY cards; and buffer to control the electromagnets via the transistor drivers (Fig. 16). The applied Yamaha PSR-1500 MIDI keyboard is of a *touch-sensitive* type, therefore according to the velocity with which the key was pressed a MIDI code is generated. A sensor under the keyboard picks up the signal correlated to the way of depressing the key and at the same time transforms it into the system input signal.

The information on pressing or releasing the key is transmitted from the keyboard through the MIDI interface in the form of 2 or 3 bytes of data:

— the first command means that data will be transmitted,

— the second byte – information on the key number within the range from 0 to 127,

— the third byte – information on the velocity of pressing the key, in the range from 1 to 127.

The information related to the key number is essential because of the relation between the size of the pipe and the articulation artefacts. In traditional, mechanical organs, articulation features appear mostly in low tones. The sound rise in large pipes may be fast or slow, so it is possible to hear the differences in the articulated sounds. Small pipes, because of their size, are excited by the wind blow very quickly and speak nearly always in the same way.

The above information is decoded by the computer through a MIDI decoding procedure. Obtained values are periodically transmitted to the fuzzy logic control system at the speed of 31.25 kBaud. The total transmission time $t$ (Eq. (4.3)) consists of at least three delays, namely:

— $t_1$ – connected to the data transmission from the keyboard to the MIDI card:

$$t_1 = \frac{20 \text{ bit}}{31250 \text{ bit/s}} = 640 \text{ µs};$$

— $t_2$ – corresponds to the data processing in the MIDI card:

$$t_2 \approx 30 \text{ µs};$$

— $t_3$ – needed for the data processing in the FUZZY microprocessor card: $t_3 \approx 8$ µs

$$t \approx t_1 + t_2 + t_3 \approx 640 \text{ µs} + 30 \text{ µs} + 8 \text{ µs} \approx 678 \text{ µs}. \tag{4.3}$$

As is shown in Fig. 16, three parallel connected electromagnets are applied to drive the pallet opening the air inflow. The electromagnets are switched on and driven by the current, the value of which is defined by the fuzzy rule system. Thus, any key motion rates will be translated into the way of opening the valve, and in consequence into the building of air pressure in the pipe that is decisive to the character of the rising sound.

Two parameters that are extracted periodically from the MIDI code, namely the key number and the velocity, create two fuzzy inputs, labeled as:

INPUTS: *KEY_NUMBER; VELOCITY*,

and output is associated with the current applied to electromagnet coils and is denoted CURRENT. Corresponding membership functions are labeled as follows:

OUTPUT: *LOW_CURRENT; MEDIUM_CURRENT; HIGH_CURRENT.*

The fuzzifiers were named as follows:

FUZZIFIERS: for *KEY_NUMBER* and *VELOCITY*: – *LOW*,
– *MEDIUM*,
– *HIGH.*

Fig. 14. Fuzzy logic-based control system for a pipe organ.

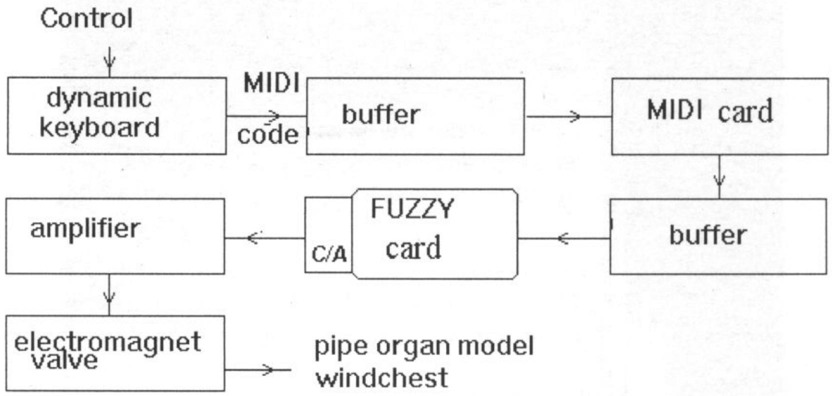



Fig. 15. Block diagram of the control system.

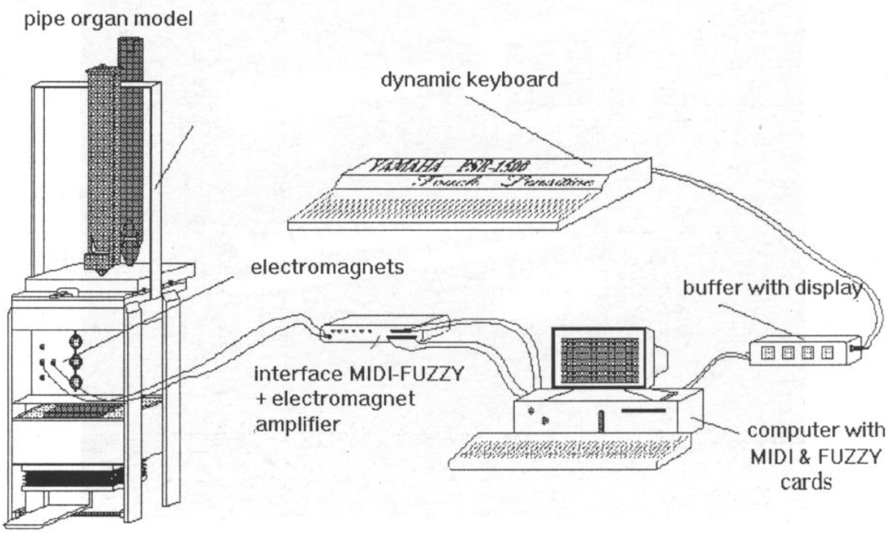



Fig. 16. Lay-out of the fuzzy logic-based control system configuration.

**Table 2.** Mapping of the keyboard.

| *KEY_NUMBER* | CENTER | WIDTH |
|---|---|---|
| *LOW* | 30 | 29 |
| *MEDIUM* | 70 | 25 |
| *HIGH* | 100 | 27 |

**Table 3.** Velocity mapping.

| *VELOCITY* | CENTER | WIDTH |
|---|---|---|
| *LOW* | 30 | 29 |
| *MEDIUM* | 70 | 15 |
| *HIGH* | 101 | 26 |

The output of the system is set at the beginning to the value equivalent to 0. The MIDI code assigns the keys with numbers from a range starting from 0 (when no key is pressed) to 127. The mapping of the keyboard was reflected as *KEY_NUMBER*, and is presented in Table 2. The velocity values are represented as in Table 3.

The above listed values (Tab. 2 and 3) were set experimentally. The performed experiments allow one to show the plot of membership functions corresponding to the input *KEY_NUMBER* and *VELOCITY* and *CURRENT* denoted as OUTPUT (Fig. 17). As can be seen from Fig. 17, triangular membership functions are employed in the fuzzy controller.

The inputs and fuzzifiers are producing terms that are used in the following rules:

RULES:

**if** *KEY_NUMBER* **is** *OFF* **then** 0

**if** *VELOCITY* **is** *OFF* **then** 0

**if** *KEY_NUMBER* **is** *LOW* **and** *VELOCITY* **is** *LOW* **then** *LOW_CURRENT*

**if** *KEY_NUMBER* **is** *MEDIUM* **and** *VELOCITY* **is** *LOW* **then** *LOW_CURRENT*

**if** *KEY_NUMBER* **is** *HIGH* **and** *VELOCITY* **is** *LOW* **then** *MEDIUM_CURRENT*

**if** *KEY_NUMBER* **is** *LOW* **and** *VELOCITY* **is** *MEDIUM* **then** *MEDIUM_CURRENT*

**if** *KEY_NUMBER* **is** *MEDIUM* **and** *VELOCITY* **is** *MEDIUM* **then** *MEDIUM_CURRENT*

**if** *KEY_NUMBER* **is** *HIGH* **and** *VELOCITY* **is** *MEDIUM* **then** *HIGH_CURRENT*

**if** *KEY_NUMBER* **is** *LOW* **and** *VELOCITY* **is** *HIGH* **then** *HIGH_CURRENT*

**if** *KEY_NUMBER* **is** *MEDIUM* **and** *VELOCITY* **is** *HIGH* **then** *HIGH_CURRENT*

**if** *KEY_NUMBER* **is** *HIGH* **and** *VELOCITY* **is** *HIGH* **then** *HIGH_CURRENT*.

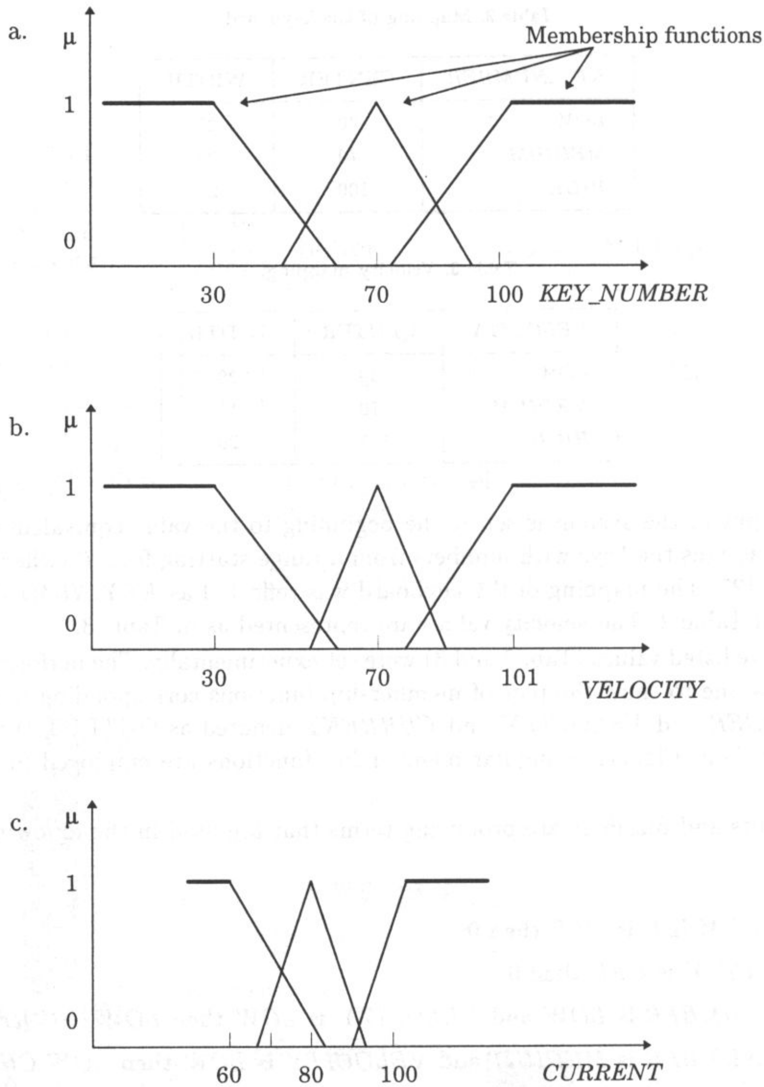



Fig. 17. Membership functions corresponding to the *VELOCITY* (a), *KEY_NUMBER* (b) inputs and CURRENT denoted as output (c), where $\mu$ – degree of membership.

Each rule produces a number which is calculated according to fuzzy logic principles from the cross-section of the input values with the membership functions [13] (see Fig. 17). The winning rule is one that has the highest value assigned during the calculations. On the basis of the adopted terms, the numerical values are converted to the respective current which is driving the electromagnets. This means that the lowest output value causes the slowest opening of the valve, while other values appearing on the output, which match other terms, result in a faster opening of the valve.

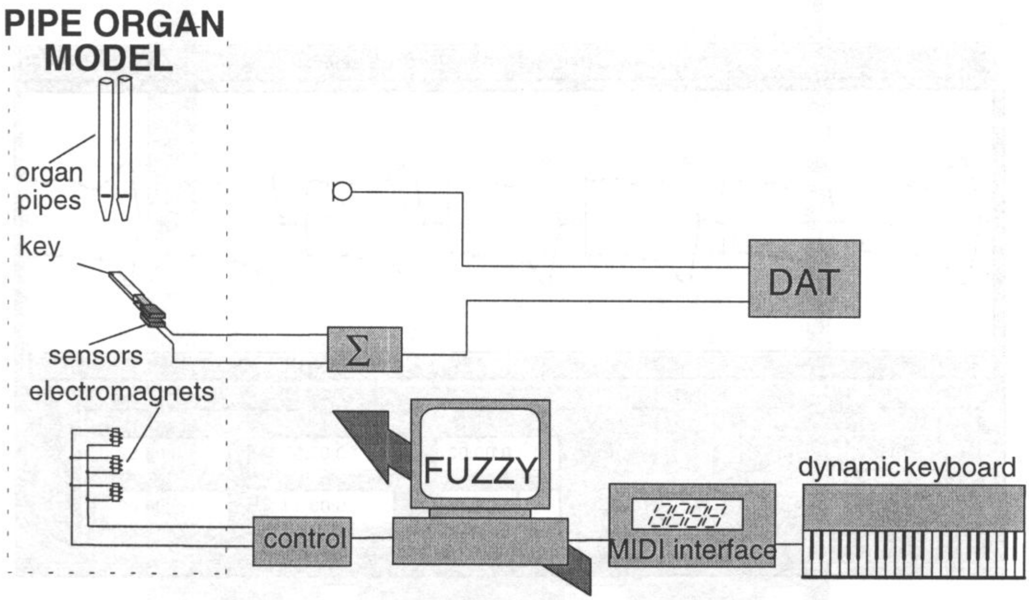


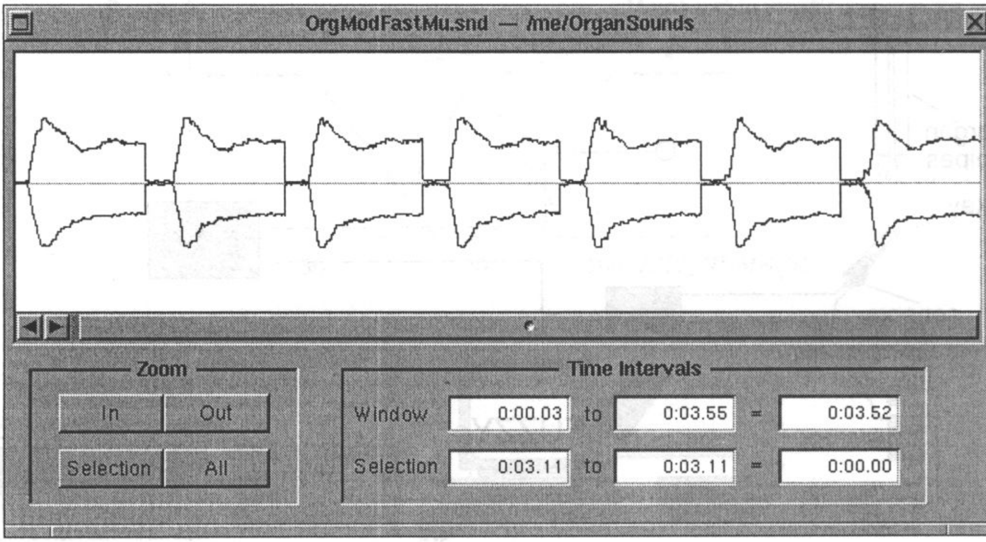

Fig. 18. Block diagram of the recording system of the pipe organ model.

Recordings of the signals generated by the model were made based on the system whose block diagram is presented in Fig. 18. A pair of sensors were attached to the key, and are activated electrically. The input of the system was controlled through a touch-sensitive keyboard. Impulses from sensors responsible for the time of depressing the key in the model were registered. The value of the velocity of depressing the key was read from the MIDI interface display. The output signal from the control system was recorded on the left channel of the tape recorder, while the sound of the pipe was registered on the right channel.

Examples of analyses of the time- and frequency-domain characteristics of the recorded sounds are presented in Fig. 19 and 20. The plots show the differences that are visible in the time representation of the analyzed sounds, as well as in the representation of waterfall plots, respectively for fast (Fig. 19 a and 20 a) and slow (Fig. 19 b and 20 b) opening of the valve. Both spectral characteristics differ mainly in the behavior of the second harmonic which grows very quickly in the case of pressing the key quickly and slowly in the other case. There are also other discrepancies for the sounds presented. It is easy to observe that the fundamental is much weaker when depressing the key quickly. The arrows "A" in Fig. 20 show the starting point of the rising of fundamentals, whereas the arrows "B" show the rising of second harmonics.

These results show a clear similarity between previously obtained analyses. Therefore, it may be said that the constructed fuzzy logic control system for a pipe organ action responds properly depending on differentiated musical articulation.

a.




b.

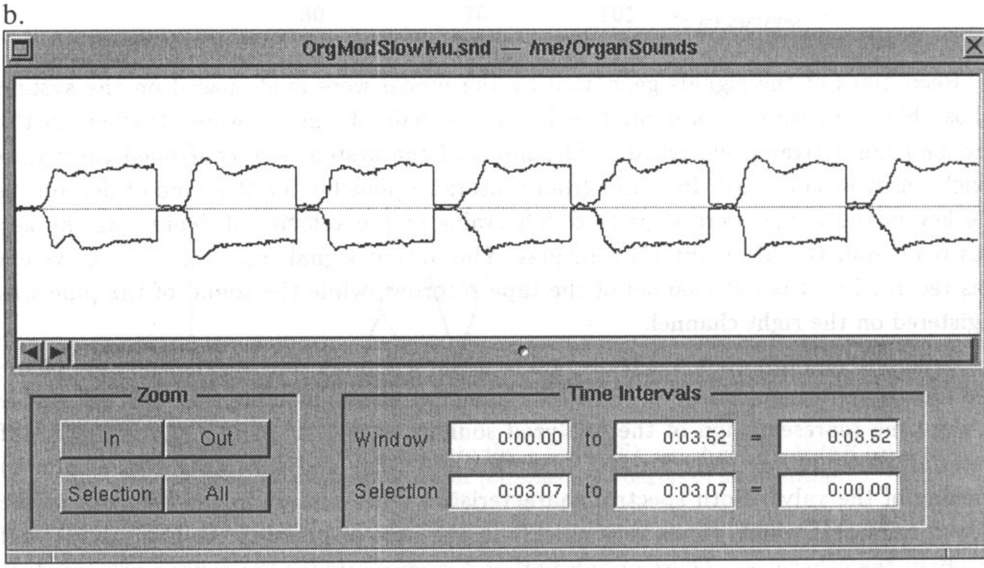



Fig. 19. Analyses of time-domain characteristics of sounds of Principal 8′ in the case of: a) fast opening of the valve, b) slow opening of the valve.

a.

b.

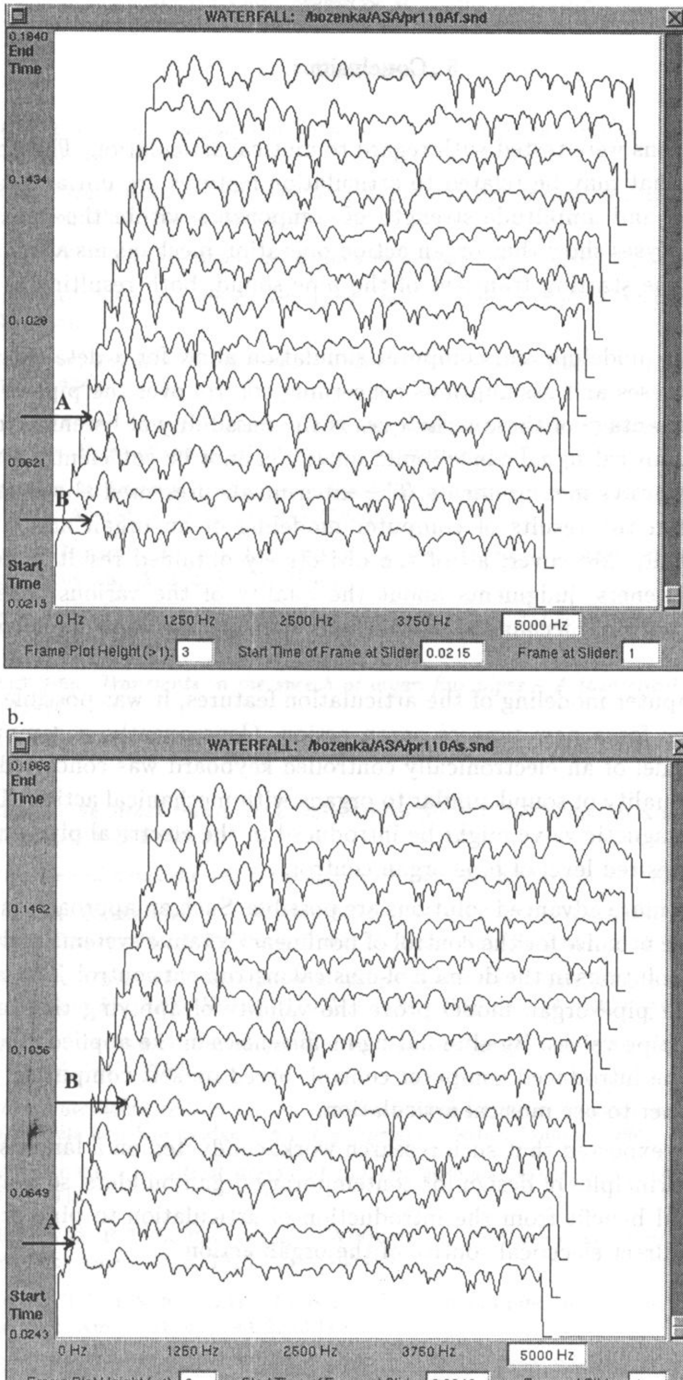



Fig. 20. Analyses of frequency-domain characteristics of sounds of Principal 8′ in the case of: a) fast opening of the valve, b) slow opening of the valve.

## 5. Conclusions

The organ actions were tested with regard to musical articulation. The physical pipe sound properties that may be related to articulation features are initial delay, starting transient duration and amplitude strength of components within the duration of the transient. The analyses show that organ action operation mechanisms affect mainly the initial delay and the starting transient of the pipe sound, both resulting in a different sound quality.

Both computer modeling and computer simulation allow for a detailed verification of different hypotheses and assumptions concerning control over the pipe organ sound. The additional advantage of these techniques is the possibility of listening to extracted fragments of the musical signal, since sound quality cannot be sufficiently assessed only on the basis of objective measurements. The experiments presented above showed good correlation between the results of computer modeling of an organ action and those obtained analytically. Moreover, all of the objectively obtained results confirmed the musicians' and listeners' judgments about the quality of the various types of organ control systems, with a mechanical tracker action being the most preferred in their opinions.

Based on computer modeling of the articulation features, it was possible to propose technical solutions for a new type of organ action. Consequently, a computer action system with a model of an electronically controlled keyboard was conceived and simulated, showing a quality of sound similar to organs with mechanical action. Therefore, a four-step electromagnetic valve might be introduced in the electrical pipe organ action, approaching the desired level of pipe organ control.

However, even more advanced solutions are possible. Such an approach as fuzzy logic shows considerable promise for the control of nonlinear dynamic systems and may result in some practical solutions in the domain of musical instrument control. The experiments carried out on the pipe organ model prove the validity of applying this technique to controlling organ pipe valves. By eliminating inefficiencies in the applied mechanisms of electric actions, the introduced computer control, based on soft computing techniques, allows the performer to use musical articulation.

It may also be expected that such research work, conducted on a larger scale, might result in reliable principles of design for contemporary organ builders, so that musicians and listeners could benefit from the introduction of articulation to pipe organ instruments which use direct electrical control of the organ action.

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