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INVESTIGATION OF ARTICULATION FEATURES IN ORGAN PIPE SOUND

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The aim of the paper is to approach the problem of existing limitations in the articulation of sound in a pipe instrument with electromagnetic action. The importance of attack transients in articulation phenomena is examined. Hence, detailed investigations in the domain of attack transients in pipe sound were carried out. The applied methods and the results of analyses are discussed.

1. Introduction

The organ is an instrument which changes continually with durable traces left by each passing epoch on both an external structure and internal elements. No other instrument has passed so long a path of development as the organ did since the times of Ktesibos of Alexandria or those of Heron's water organ till the present times.

From the musical point of view mechanically controlled organs built in the period of baroque are still an unattainable model owing to the fact that this type of control enables possibilities for musical articulation. The contact between the organist and the pipe organ being established right at the moment of touching the key. The possibility of modifying the way in which the sound intensity increases depends on the resistance of the key, which is connected mechanically with the valve of the wind-chest and is stronger at the beginning due to the compressed air, which presses the valve against the air inlet part, then is reduced to merely a value necessary for overcoming the resistance of the return spring of the key. In the opinion of many organists this two-phase nature of resistance of the key makes it possible for the organist to modify the process of growth of the sound [1], [9].

In the course of evolution of control systems of the organ, the pneumatic, then electric systems were invented, which made the task of organ playing much easier, but introduced a "foreign force" between the key and the source of sound, thus making the performance much poorer in reflect of variety of musical articulation.

[1] Research sponsorred by Komitet Badań Naukowych (KBN) in 1992.

At this point it seems to be indispensable to give a more detailed definition of the notion of articulation, which is used in the domain of music for describing the way in which the musical fragment considered should be performed according to the musical notation. The latter term is secondary and concerns all the conventional marks describing the way of getting a tone or a chord to obtain intended acoustic effect and to emphasize the character of musical work. Principal types of articulation are denoted by conventional signs such as *staccato* (in abrupt, sharply detached manner, *Italian staccare* = to detach, to disconnect)., *spiccato* (distinctly, emphatically, *It. spiccare* — to separate, to disconnect, to speech distinctly), *legato* (smoothly, without breaks, *It. legare* — to bind), *portato* (with smooth, not abrupt separation of tones, *It. portare* — to carry), *glissando* (gliding continuously from one pitch to another, *It.*), *portamento* (slight gliding, in singing or violin playing, between two distant tones, *It.*), *tremolo* (trembling, *It. tremolare* — to tremble), *arpeggio* (striking of notes of chord in succession, *It.*, in harp-like manner) and a number of signs, among which there are those of trill, turn of grace note (*appoggiatura*), long and short [7]. As regards various kinds of music or even particular instruments, the evolution of articulation elements was independent. The style of interpretation of organ music is influenced by not only articulation notation but also the type of control system and acoustic properties of the interior in which the organ has been installed.

The aim of the present paper is to discuss results of the research carried out by authors concerning articulation problems of organ sound and analyses which have been made.

2. Analytical description of transient or organ pipe sound

The mechanism of producing vibrations in self-excited aero-acoustic systems such as flue pipes is not yet sufficiently known, the fundamental difficulty being that of efficient separation from the organ pipe system of its component parts that is the system of excitation and vibration. Those systems are connected with each other in a dynamic manner which is a result on the one hand, of contraction inside the air stream flowing out from the pipe slot, defined by the edge of languid and the lower lip of the pipe mouth and, on the other hand, a result of the action of the air column vibrating inside the body of the pipe on the transient values of the velocity vectors of particles of the air jet. Because in the organ pipe system the action of the vibrating air column is essential the mechanism of exciting vibrations in a flue pipe is defined as a process of turbulence type excitation, although the Reynolds number characterizing the flow considered does not exceed, as a rule, a critical value of 2300 which separates the laminar from turbulent flow [2].

The method for analysis of transients in organ sound, based on the nonlinear theory of generation of vibrations in a flue pipe is the subject of Fletcher's studies [2], [3]. He treats an organ pipe as a system constituting two coupled subsystems, namely a linear resonator system with an infinite number of natural vibrations the angular frequency of which is n_i and a nonlinear system of air stream with disturbances of the vortex layer about the upper lip vibrating with an angular frequency ω_i. Taking into consideration damping due to radiation of internal friction and heat conduction the former system can be described by the following second order differential equation [3]:

$$\ddot{x}_i + k_i\dot{x}_i + n_i^2 x_i = \lambda_i F(t) \tag{1}$$

where: n_i — angular frequency of the i-th mode of linear resonator, $F(t)$ — external force, x_i — displacement of the i-th vortex of the air stream, λ_i — coefficient of coupling between the pipe and the air stream, k_i — coefficient of damping.

It the amplitude of $F(t)$ is constant, and the frequency being the only variable, the amplitude of the resonance frequency is in direct proportion to the ratio λ_i/k_i and its width to k_i.

In the static case, for which it is assumed that acoustic velocity of the air stream v at the outlet of the pipe is constant, the force F can be expressed by the power series expansion:

$$F = c_0 + c_1 \cdot v + c_2 \cdot v^2 + c_3 \cdot v^3 + \dots \tag{2}$$

where: c_n — coefficients of the pressure function of the air system, v — acoustic velocity of the air stream.

In reality the pipe is a nonlinear dynamic system. Oscillations of the air column of acoustic velocity v act on the air stream leaving the inlet aperture, thus producing variations of the force F as a function of the acoustic velocity ($v \sum x_i$). The resulting pressure response is established with a certain delay δ, which is equal to the time of displacement of single vortex along the air stream, necessary for the passage across the mouth of the pipe. It should also be borne in mind that the air stream may dissipate its energy in such a manner that δ depends on the frequency. This interaction may result in a phase shift Δ. The frequency ω_i of the i-th natural vibration is related to the resonance frequency n_i, therefore the generalized equation (2) takes the form (3):

$$F(t) = \sum_{m=0}^{\infty} c_m \left[\sum_{i=1}^{\infty} \dot{x}_i \, (t - \delta_i - \Delta_i/\omega_i) \right]^m \tag{3}$$

where: δ_i — time necessary for a single vortex to be displaced along the air stream leaving the organ pipe mouth, Δ_i — phase shift.

If the feedback in the nonlinear system composed of the organ pipe and the stream is taken into account, the equations (1) and (3) can be expressed in the form:

$$\ddot{x}_i + n_i^2 \cdot x_i = f_i(\dot{x}_j) \tag{4}$$

where:

$$f_i(\dot{x}_j) = -k_i \cdot \dot{x}_i + \lambda_i \cdot F(\dot{x}_1, \dot{x}_2, \dots) \tag{5}$$

Despite the intense development of the theory of nonlinear vibrations, there is no universal method for analysis and solution of a set of nonlinear equations. In the analysis of nonlinear vibrations in the neighbourhood of equilibrium position, nonlinear systems are linearized usually by the Krylov-Bogolubov method or that of a series of small parameters or the Van-der-Pol method [4]. If the solution of nonlinear equation is an oscillalting solution with a time variable amplitude and phase, the variations being very slow, however, the method of slowly varying parameters is used. The condition of slow variation originates from the fact the solution can be obtained only if transient values varying parameters is used. The condition of slow are replaced by their average values found by integrating over a period of the vibrations. An oscillating solution can also be obtained by methods based on the principle of equilibrium of harmonics. In practice high accuracy solution cannot be obtained, however, therefore it is often necessary to use several methods simultaneously. Using the first two methods a periodic solution of the nonlinear equation is sought for in the form of a power series, the convergence of which is ensured for a sufficiently small f_i.

By reducing the original nonlinear second order equation to the form (4) and (5) the nonlinear terms can be separated, so that a periodic solution of the linear equation is obtained as a first approximation.

Assuming that f_i is sufficiently small as compared with the terms on the left-hand side of (4), the possible solution of that equation may assume the form:

$$x_i = a_i \cdot \sin(\omega_i t + \beta_i) \tag{6}$$

where: $\omega_i \simeq n_i$, a_i — amplitude, β_i — phase displacement, a_i, β_i — constants depending on the initial conditions.

For further computation it is assumed that the terms a_i and β_i are functions of time. On differentiating x_i with respect to time one obtain:

$$\dot{x}_i = a_i \cdot \omega_i \cdot \cos(\omega_i t + \beta_i) + \dot{a}_i \cdot \sin(\omega_i t + \beta_i) + a_i \cdot \dot{\beta}_i \cdot \cos(\omega_i t + \beta_i) \tag{7}$$

If the derivate $\dot{x}_i$ is to take form:

$$\dot{x}_i = a_i \cdot \omega_i \cos(\omega_i t + \beta_i) \tag{8}$$

the condition:

$$\dot{a}_i \sin(\omega_i t + \beta_i) + a_i \dot{\beta}_i \cos(\omega_i t + \beta_i) = 0 \tag{9}$$

must be satisfied. Substituting the derivates of the periodic solution into equation (4) gives, if the condition (9) is satisfied, a set of equations, from which $\dot{a}_i$ and $\dot{\beta}_i$ are found:

$$\dot{a}_i = \frac{1}{\omega_i} f_i(\dot{x}_j) \cos(\omega_i t + \beta_i) - \frac{a_i(n_i^2 - \omega_i^2)}{\omega_i} \cdot \sin(\omega_i t + \beta_i) \cdot \cos(\omega_i t + \beta_i) \tag{10}$$

$$\dot{\beta}_i = \frac{1}{a_i \omega_i} \cdot f_i(\dot{x}_j) \sin(\omega_i t + \beta_i) + \frac{(n_i^2 - \omega_i^2)}{\omega_i} \cdot \sin^2(\omega_i t + \beta_i) \tag{11}$$

If the functions $\dot{a}_i$, $\dot{\beta}_i$ are replaced by their average values, which will be denoted by $\langle \dot{a}_i \rangle$ and $\langle \dot{\beta}_i \rangle$, respectively, and which are found by integrating the right-hand forms of the above equations over one vibration period, one obtain:

$$\langle \dot{a}_i \rangle = \frac{1}{\omega_i} \cdot \langle f_i(\dot{x}_j) \cos(\omega_i t + \beta_i) \rangle \tag{12}$$

$$\langle \dot{\beta}_i \rangle = -\frac{1}{a_i \omega_i} \cdot \langle f_i(\dot{x}_j) \sin(\omega_i t + \beta_i) \rangle + \frac{(n_i^2 - \omega_i^2)}{2\omega_i} \tag{13}$$

Assuming that the vibrations are stationary these functions may be expanded in Fourier series. In this case the aim of the integration operation is to separate the harmonics ω_i from the functions $f_i(\dot{x}_j)$.

A condition of the nonlinear set of equations of oscillations in an organ pipe being solvable in the harmonic form (6) with the parameters a_i and β_i varying slowly in time, is that all the secular terms in (12) and (13), that is terms of the type $t\sin\omega t$ and $t\cos\omega t$, which are markedly dependent on time are to be neglected. Those terms, the character of which does not vary for a few periods are retained. Moreover, the average values $\langle \dot{a}_i \rangle$ and $\langle \dot{\beta}_i \rangle$ should be sufficiently small as compared with a_i, ω_i.

The averaging operation which has been performed in equations (12) and (13) as a first approximation confirmes the variability of ω to the type of $\omega \pm \omega_i$. Then, the slowly varying functions for which the condition $\omega \pm \omega_i \simeq 0$ is satisfied being the only retained, the simplification of the form of solution becomes considerable. To illustrate the form of the expressions (12) and (13) which have been obtained, only the first three modes of the pipe are taken into account, for which $n_i \cong i \cdot n_1$, the characteristic of the air stream being expanded up to the third power terms. The d/dt derivative of the phase angle $(\omega_i t + \beta_i)$ may be considered as an instantaneous value of the pulsation which is, for the i-th mode $(\omega_i + \dot{\beta}_i)$. From the condition of the natural vibrations preserving a strictly harmonic relationship and the condition of β being independent of time one obtain, on substituting $n_1 = (\omega_1 + \dot{\beta}_1)$ and, similarly $n_i = i \cdot (\omega_1 + \dot{\beta}_1)$, the condition:

$$\omega_i + \dot{\beta}_i = i \cdot (\omega_1 + \dot{\beta}_1) \tag{14}$$

By analysing consecutive stages of organ sound "non-musical" modes can be observed in a steady state and in the phase of growth of the sound as well. They are connected with the fact that the satisfaction of the condition $\omega_i = n_i$ is only approximate and, therefore, with the existence of interrelations between particular components of the sound.

Assuming, after Fletcher, that the attack transient behaviour of the air stream can be described in the form [3]:

$$p(t) = p_0 + (p_1 - p_0) \exp(-t/\tau) \tag{15}$$

where: $p(t)$ — pressure of the air stream in the growing stage, p_1 — maximum pressure, p_0 — steady state pressure, τ — time necessary for the pressure to obtain the value p_0, The initial conditions are:

$$\begin{aligned} v_i &\simeq (0.5p_1/i)\sin(n_i t) \\ a_i^0 &= 0.5p_1/i \cdot n_i, \quad \beta_i^0 = -\pi/2, \\ \Delta &\simeq \pi \\ \omega_i &= n_i \end{aligned} \tag{16}$$

Particular values of the coefficients are denoted by: l, c_0, c_1, c_2, c_3, n_1, n_2, n_3, k_1, k_2, k_3, λ_1, λ_2, λ_3, γ, δ,
where: γ — scale factor for the interaction between the air column and the air stream, δ — propagation delay.

As a result this makes possible numerical sulution of the equations (12) and (13).

The expression (15) can be related to the way of opening the air inlet to the pipe. If $p_1 \gg p_0$ it may be assumed that the valve is opened in an abrupt manner, thus producing a distinct pressure peak. If $p_1 = p_0$, the sound grows rapidly, the steady state being reached immediately. In the third case, $p_1 \ll p_0$, the growth of the transient is slow [3].

Showing the dependence of the growing phase of organ sound on the way of opening the air flow, Fletcher does not relate, however, those phenomena directly to the problem of musical articulation. In view of the lack of appropriate references in the literature this problem requires an original method of investigation to be devised. The related problems will be discussed in what follows.

3. Methods for studying articulation parameters

In view of the lack of verified techniques of recording articulation parameters of organ playing such investigation was conducted, under laboratory conditions, then the same method was used for studying various musical articulation of organ sound with instruments located in real interiors. The method proposed for studying the phenomenon of musical articulation is based on the measurement of the time of displacement of the key from the position at the rest to state of full depression with simultaneous observation of the process of the growing sound.

3.1. The method of extraction of articulation parameters

To extract a parameter of organ sound related to the problem of musical articulation one should first analyze the articulation features transferred by the organ player on the motion of the key. As mentioned in Sec. 1 musical articulation may be referred to all the conventional marks contained in the musical notation (tabulature), therefore indirectly, by translating them into language of physical phenomena, to the force acting on the key, the velocity of its motion and possibly, the use by the player of a means consisting in stopping momentarily the motion of the key in various positions during the action of key pressing. However, the latter idea cannot be accepted due to the fact that during the stop of the valve in a position of partial opening, the pipe sounds out of tune. This fact has been cofirmed by organists, who consider this way of organ playing to be incorrect and, thereofre unuseful from the point of view of investigation of articulation features of organ playing.

Now, the study of the valve system with the electromagnetic control systems shows that the force may be also eliminated from the considerations [1], [8]. The use of a greater force of pressure on the key cannot influence the way in which the pipe blowing process is started except the case in which greater force means greater velocity of motion of the key. Thus, it is the relation between the velocity of motion of the key and the sound generated by the pipe which will be assumed in the present consideration as a basis for studying objective features of articulation. As a consequence the velocity of touch on the key, which should not as a rule remain in a position corresponding to the half-open position of the valve may be replaced with another parameter, easier to measure, that is the time of displacement from the rest position to the bottom position, which is that of the state of full depression [5].

From the above assumptions it follows that the system of recording measurement signals should ensure synchronous record of the displacement time of the key and the sound of the organ. The diagram of the recording system for the purpose of investigation into the objective features of articulation in organ music is shown in Fig. 1.

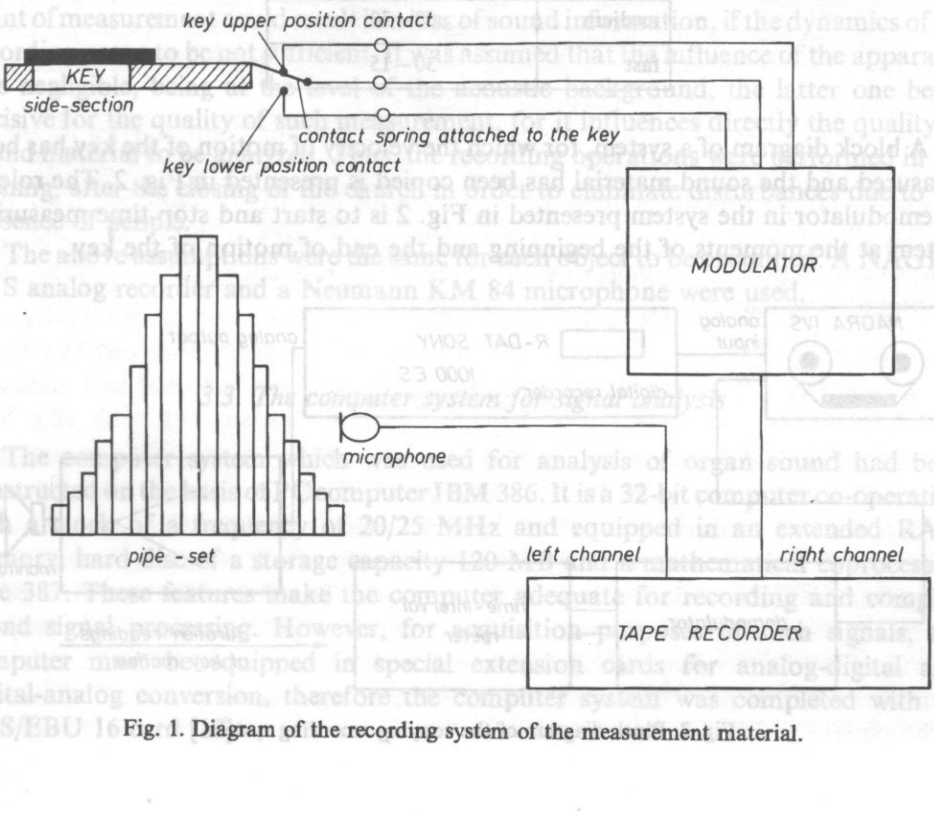

Fig. 1. Diagram of the recording system of the measurement material.

The role of modulator in Fig. 1 is that of generating a rectangular signal at a frequency of about 10 kHz over that period of time during which the middle spring of the change-over switch resting upon a of the key is not in contact with lateral sets of contacts. This corresponds to the case in which the key is between the position of rest and the bottom position that is the state of maximum key depression.

In the first phase of the carried investigation the changing over time of the key was recorded in a synchronous manner with the organ sound in the case slow and fast motion of the key. The sound material was recorded on a tape recorder, then copied on a R-DAT digital recorder thus making it possible to mark the beginnings of particular fragments for the purpose of automatic searching. Some preliminary analyses were also made, the aim of which was to study the relation between the velocity of displacement of the key and the articulation. This enables to fix the values of the time interval corresponding to the velocity of displacement of the key. Table 1 shows values of time intervals for a slow, moderate and fast touch on the key.

Table 1. Speed of key motion as expressed in terms of the time of travel between the initial and final position of the key

Key speed	Duration of travel [ms]
slow	90 – 50
medium	50 – 30
fast	30 – 15

A block diagram of a system, for which the velocity of motion of the key has been measured and the sound material has been copied is presented in Fig. 2. The role of a demodulator in the system presented in Fig. 2 is to start and stop time measuring system at the moments of the beginning and the end of motion of the key.

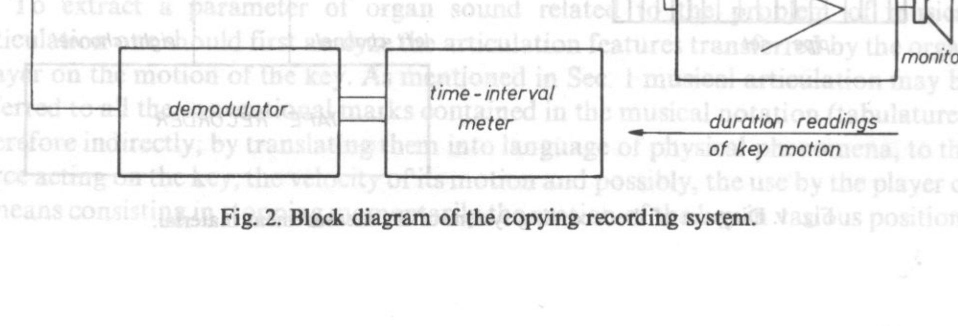

Fig. 2. Block diagram of the copying recording system.

3.2. Investigation of organ sounds

Organs with mechanical tracker action (St. Nicholas Church and St. Mary's Basilica) and, for comparison, organs with electric and electropneumatic control (Oliva Cathedral) were selected for measurements.

The organ stops to be recorded were selected taking into consideration particular properties of the organs and also repeatability of the tests. The fundamental organ stop is Principal, an open cylindrical flue pipe. In addition flute pipes (Bourdon, Gedackt) can be found in every organ, therefore the investigation was confined to recording the sound of pipes of the two types mentioned above. For each voice the tone *a* was recorded on an analog tape recorder for each octave beginning from the lowest. In order to facilitate latter analyses a single tone was recorded.

Another factor decisive for the quality of measurements is the location of the microphone, which depends on the size of the instrument, the arrangement of stops in the organ and the acoustics of the interior. Making use of the information available on the location of an organ pipe, the microphone was installed at the distance not greater than 2 m from the pipe examined in the near field of the organ (the average critical radius being about 3.8 m for St. Nicholas' Church, 4.7 m for the Oliva Cathedral and 5.7 m for the St. Mary's Basilica) having in view recording of the sound heard directly by the organist under normal working conditions, because the choice of a static central point of measurement could result in a loss of sound information, if the dynamics of the recording prove to be not sufficient. It was assumed that the influence of the apparatus was negligible, being at the level of the acoustic background, the latter one being decisive for the quality of such measurement, for it influences directly the quality of sound material to be analyzed. Thus, the recording operations were performed in the evening, after the closing of the church in order to eliminate disturbances due to the presence of people.

The above assumptions were the same for each object to be examined. A NAGRA IV S analog recorder and a Neumann KM 84 microphone were used.

3.3. The computer system for signal analysis

The computer system which was used for analysis of organ sound had been constructed on the basis of PC computer IBM 386. It is a 32-bit computer co-operating with a clock of a frequency of 20/25 MHz and equipped in an extended RAM memory, hard disc of a storage capacity 120 MB and a mathematical coprocessor, type 387. These features make the computer adequate for recording and complex sound signal processing. However, for acquisition purposes of such signals, the computer must be equipped in special extension cards for analog-digital and digital-analog conversion, therefore the computer system was completed with an AES/EBU 16 card [10].

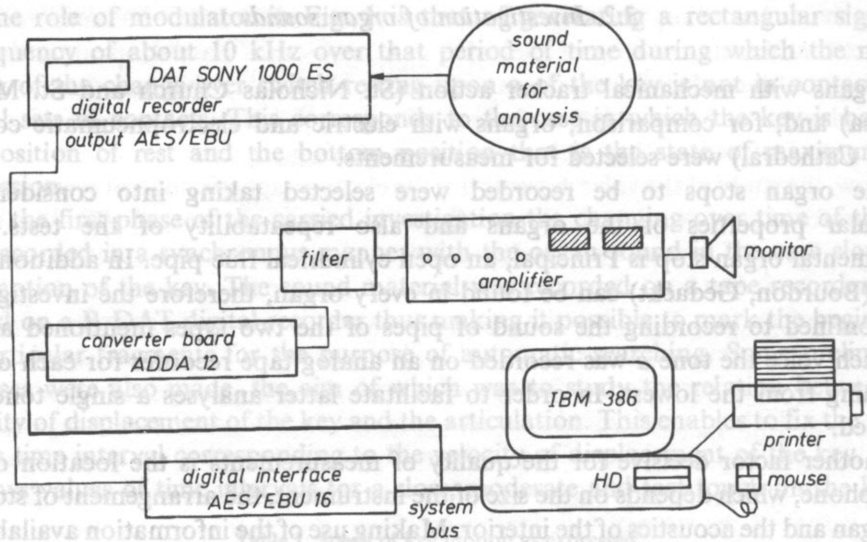

Fig. 3. Block diagram of the computer analyzing system.

A block diagram of the computer system is shown in Fig. 3. This system was designed at the Department of Sound Engineering, Gdańsk Technical University, and constitutes, together with a bundle of fundamental operational programs a necessary basis for analysis of sound signals. The programs mentioned include procedures written in Turbo Pascal and Turbo C languages [6].

The sound material for analysis is introduced into the computer by means of a NAGRA IV S analog recorder or a R-DAT digital tape recorder. In the first case analog-digital conversion is achieved by means of systems of modified card type ADDA 12 and in the other by using the internal converter of the DAT. Computer analysis makes possible visualization of sound with the accuracy to one sample with a sampling frequency of 12 or 24 kHz, as required.

4. Analysis of the results

First of all, one should answer the question as to what are the parameters describing a sound as regards the time and the spectrum which may be decisive for the articulation phenomenon. In the spectral structure of the sound which was defined earlier as a sequence of three stages, namely attack transient, steady state, decay transient, one should above all discern those features which can be used to determine the differences between sounds, therefore also the time and way of growth of particular harmonics, the duration of the transient and the delay of particular components with reference to the moment of initiation of air vibrations in the pipe.

From among all the organ sounds which had been examined only those were selected for analysis, which are representative as examples of behaviour of flue stops under definite articulation conditions.

Figure 4 illustrates the time variation of the tone *a* (110 Hz) of a Principal 8′ pipe of the Organ of St. Nicholas Church for slow and rapid touch on the key. Confrontation of the two time characteristics shows clearly the differences during

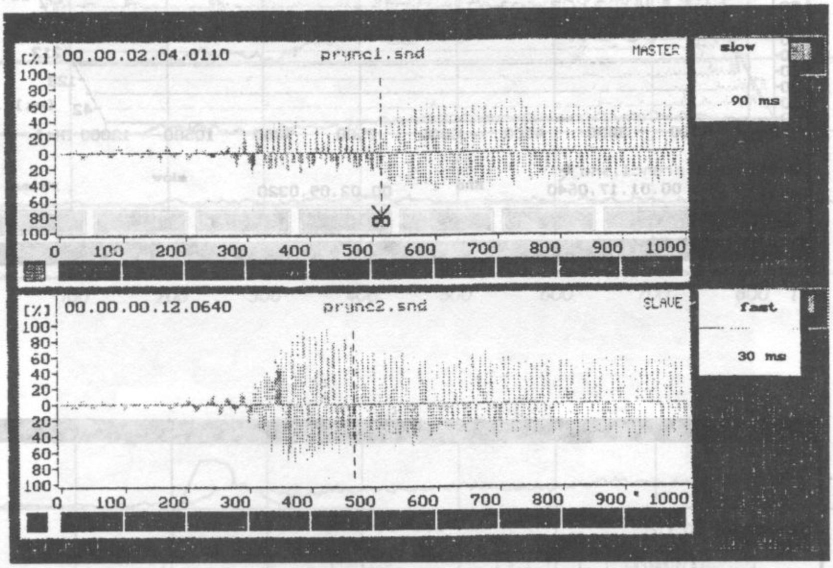

Fig. 4. Time characteristics of the tone *a*, Principal 8′, the organ of ST. Nicholas' Church.

the stage of growth of the sound. The fact of the fluctuations in the steady state being small confirms the supposition that the features of the articulation are connected above all with the process of growth of the sound. The computer system used for analysis [6] enables to cut out precisely transients for further analysis. Such an operation does not result in any observable degradation of the quality of the phonic signal. The cursor in Fig. 4 marks the point where the attack transient has been cut out from the signal recorded. Subsequent figures (Fig. 5.a. and 5.b) show the spectral characteristics of both transients. The selected fragments show differences in the way of growth of the sound which has also been confirmed by the analysis of the evolution of the sound of particular components (Fig. 6) and is particularly distinct in the histograms of Fig. 7. From the above observations one can easily indicate those features which are different for the same sound depending on the touch on the key being slow or rapid. The most essential parameter differentiating the sound tested is the way of growth of the first two components. If the touch on the key is slow the fundamental and the second harmonic begin at the same moment and grow slowly and smoothly. The overblown state with two local maxima of the second harmonic which is typical

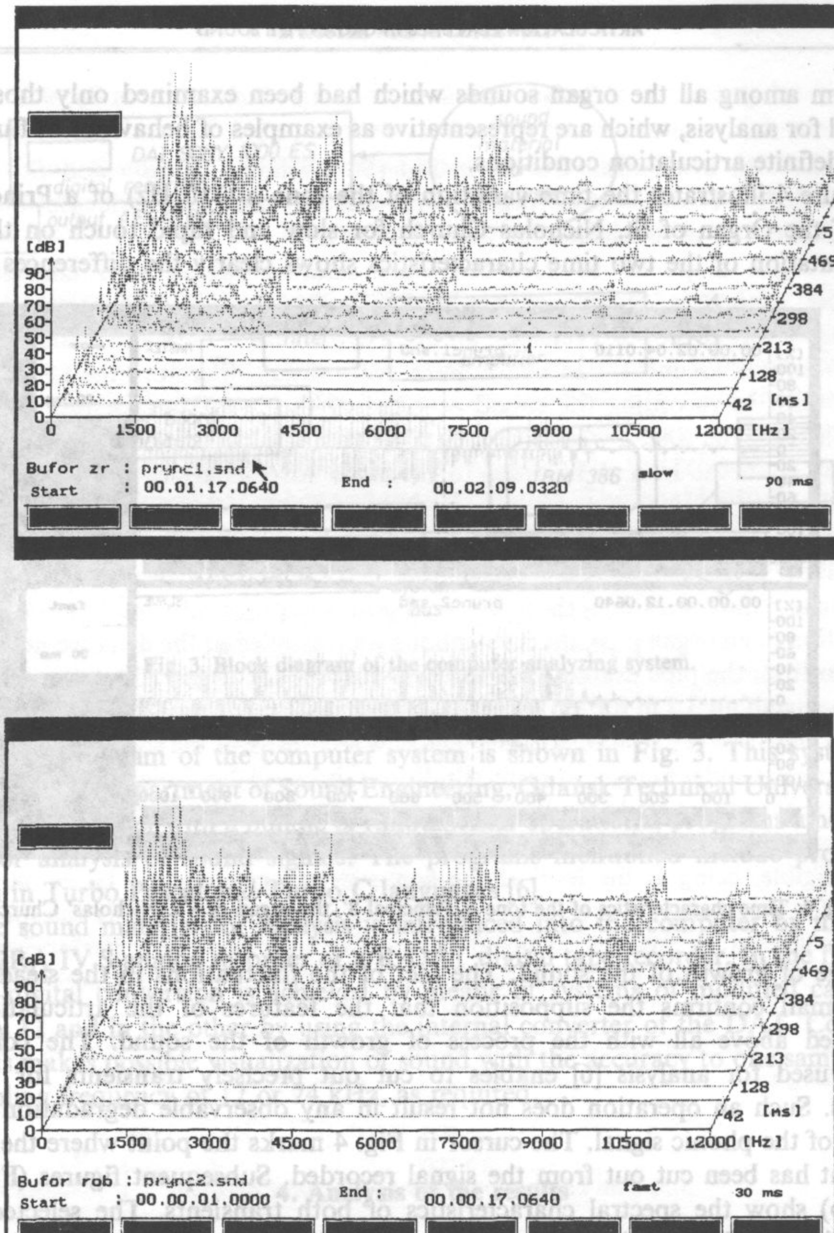

Fig. 5.a. and 5.b. Spectral characteristics of transients of the tone *a*, Principal 8′, the organ of St. Nicholas' Church.

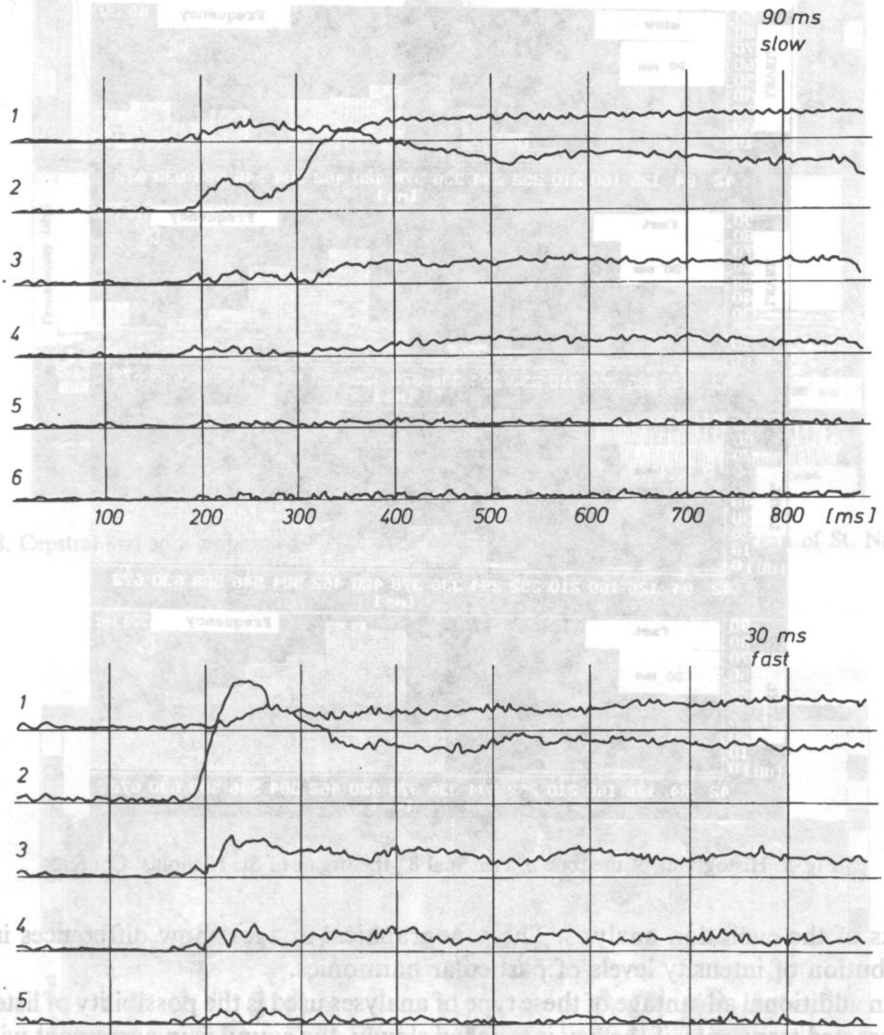

Fig. 6. Evolution analysis of the tone *a* in the case of slow and rapid touch on the key, Principal 8′, the organ of ST. Nicholas' Church.

for this class of organ stops is visible, nevertheless its amplitude remaininsiginificant. In the case of rapid motion of the key the second component is the first of all harmonics to start, while the fundamental is delayed by about 30 ms. The growth of the slope of the second harmonic is immediate and decided and exceeds considerably the amplitude of the fundamental. The capstral and sonographical analysis of the same sounds (Fig. 8) and the LPC (*Linear Predictive Coding*) sonographical analysis (Fig. 9) confirm the

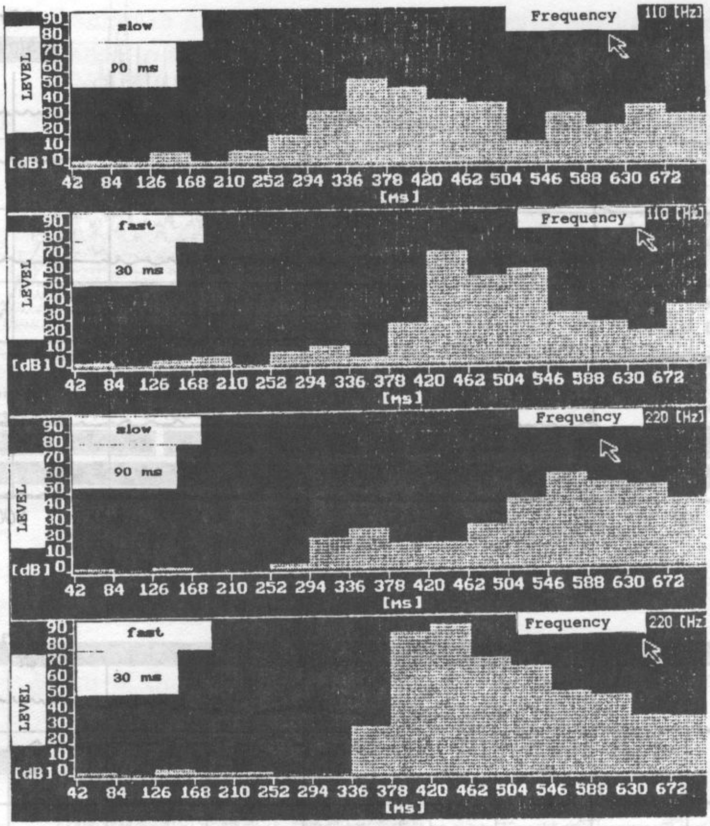

Fig. 7. Histograms of the tone *a*, Principal 8′, the organ of St. Nicholas' Church.

results of the evolution analysis. The sonographical images show differences in the distribution of intensity levels of particular harmonics.

An additional advantage of these type of analyses used is the possibility of listening to extracted transients: if the key is touched slowly, the sound is in agreement with its fundamental; if the touch is rapid the tone is by one octave higher. Multiple listening to the cut out fragments of the sound records enables to state that the impression of the pitch being correct of the proper tune having been reached occurs only after some 250 ms. The results observed confirm the hypothesis on the possibility of musical articulation in organs with mechanical tracker action.

By examining the results of evolution analysis and FFT analysis it was observed that the differences between the cases of slow and rapid touch on the key are not significant for higher tones. However, the time variation and the sonographical analysis made enable one to obtain an image of those differences (Fig. 10 to 12).

The studies and analyses of organ sounds in St. Mary's Basilica show agreement with those obtained in St. Nicholas' Church.

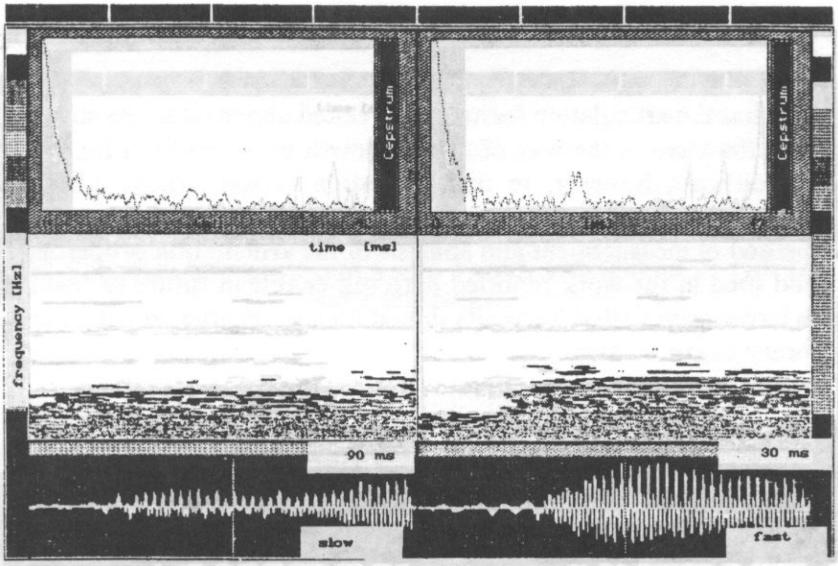

Fig. 8. Cepstral and sonographical FFT analysis of the tone *a*, Principal 8′, the organ of St. Nicholas' Church.

Fig. 9. LPC sonographical analysis of the tone *a*, Principal 8′, the organ of St. Nicholas' Church.

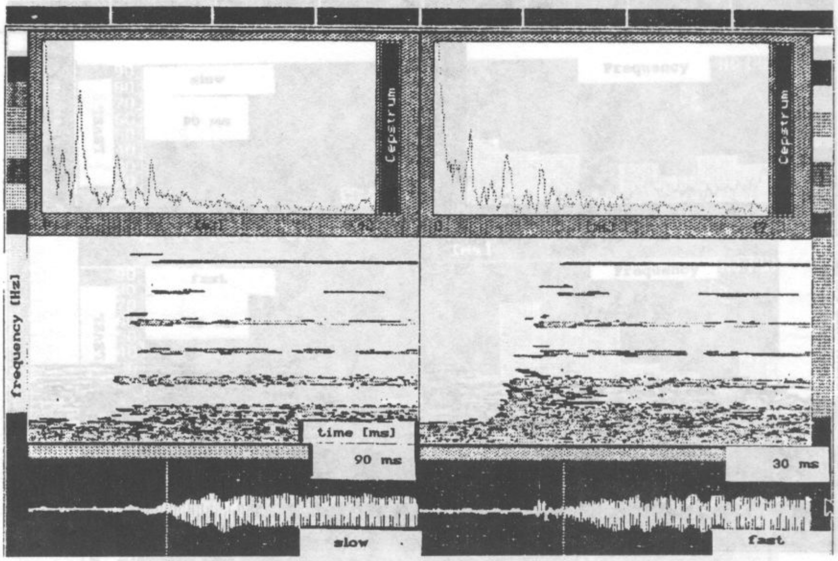

Fig. 10.Sonographical and cepstral analysis of the tone a^1, Principal 8′, the organ of St. Nicholas' Church.

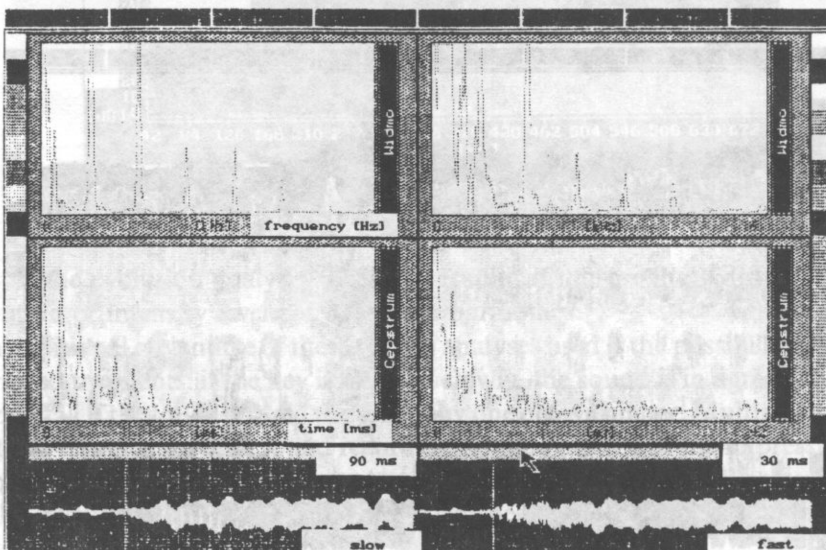

Fig. 11. Time characteristics of the tone a^2, cepstral and spectral analyses, Principal 8′, the organ of St. Nicholas' Church.

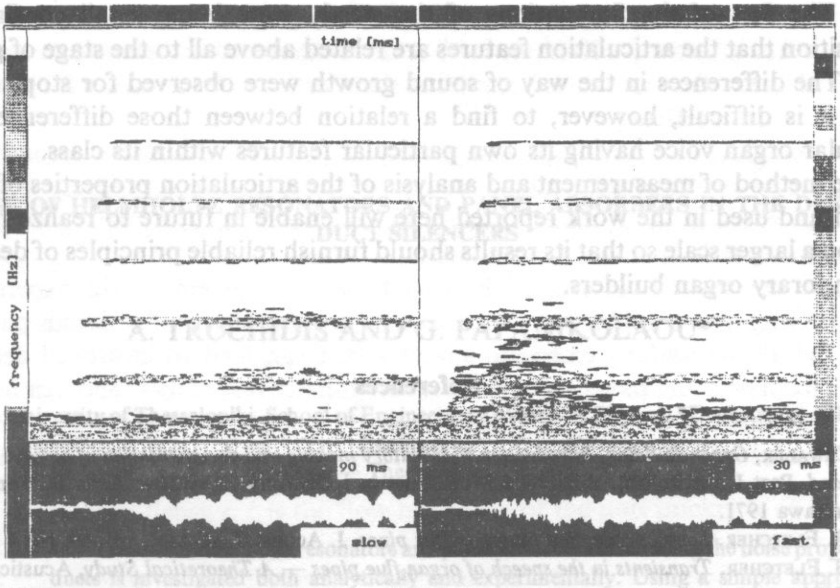

Fig. 12. Sonographical analysis of the tone a^2, Principal 8', the organ of St. Nicholas' Church.

5. Conclusions

Theoretical considerations and experimental studies and analyses of the problem of quality of organ sound and further of the quality of the control systems enable one to draw the following conclusions. Investigations carried out have confirmed the opinion expressed by musicians that the musical articulation of various kinds can be achieved in organs with mechanical tracker action.

— Because the most advanced methods of analytical description of the phenomena of excitation of vibrations in an organ pipe discussed in the introductory part of the present paper are unable to describe in a direct manner the articulation differences in growth of the sound, there remains only the experimental way of studying those processes, which was undertaken in the work reported in the present paper.

— Multiple listening examinations of cut out fragments of the sound records enabled one to state that the impression of the correct pitch being attained occurs only with a delay of about 250 ms. The results observed confirm the hypothesis on the possibility of musical articulation with organs having mechanical tracker action.

— The possibility of listening to the extracted transients of the fundamental of organ stop, namely Principal enables to state that if the key is touched slowly the sound is in agreement with the fundamental pitch. If the touch is rapid, the transient sounds by one octave higher.

— As a result of the experiments performed some differences have been observed in the way in which the transients grow, depending on whether the key is touched slowly or rapidly.

— The fact of the fluctuations of the steady state being small confirms the supposition that the articulation features are related above all to the stage of growth.

— The differences in the way of sound growth were observed for stops of both kinds, it is difficult, however, to find a relation between those differences, each particular organ voice having its own particular features within its class.

The method of measurement and analysis of the articulation properties of organs devised and used in the work reported here will enable in future to realize research work on a larger scale so that its results should furnish reliable principles of design for contemporary organ builders.

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