Tomasz KĄDZIOŁKA[1], Sławomir KOWALSKI[2], Tomasz MOŃKO[3]

[1] State University of Applied Sciences in Nowy Sącz, Institute of Technology, 33-300 Nowy Sącz, Zamenhofa 1a street, e-mail: tkadziolka@pwsz-ns.edu.pl
[2] State University of Applied Sciences in Nowy Sącz, Institute of Technology, 33-300 Nowy Sącz, Zamenhofa 1a street, e-mail: skowalski@pwsz-ns.edu.pl
[3] University of Humanities and Economics in Lodz, 90-212 Łódź, 26 Sterlinga street, e-mail: mail@tomaszmonko.com

Pipe organ evolution. From mechanical to mechatronical subsysystems

Abstract

This document discusses the use of mechatronic solutions in pipe organs. This article is the first in a series, in which the authors present a historical view of pipe organs, as well as their development. It is also an explanation of new mechatronic solutions used in modern pipe instruments, ensuring the organist's intended sounds are delivered. The registration of the instrument, both before and after performance, is explored in terms of the usage of systems.

Key words: pipe organs, windchest, registration of the instrument.

Ewolucja organów piszczałkowych. Od podsystemów mechanicznych do mechatronicznych

Streszczenie

Praca przedstawia zastosowanie rozwiązań mechatronicznych w organach piszczałkowych. Jest to pierwszy artykuł z tego cyklu, w którym autorzy zaprezentowali rys historyczny organów piszczałkowych, a także ich rozwój. Podjęta została też próba opisania nowych rozwiązań mechatronicznych, stosowanych we współczesnych instrumentach piszczałkowych, które nadają im możliwość odpowiedniego, zgodnego z wolą organisty, wydawania dźwięku. Nie bez znaczenia pozostaje także aspekt rejestrowania instrumentu zarówno przed, jak i w trakcie wykonywania utworu. Autorzy postarali się udzielić odpowiedzi na pytanie zawarte w tytule niniejszej pracy.

Słowa kluczowe: organy piszczałkowe, wiatrownica, rejestracja instrumentu.

1. Historical view on pipe organs

The genesis of the pipe organ dates back nearly five thousand years (Erdman, 1989). During this period, the Chinese built an instrument called cheng, made of bamboo pipes set on a windchest. Since this instrument was not equipped with a keyboard, the person playing it regulated the supply of air to the pipes by plugging the holes in the windchest with his fingers.

In the third century BC, the Greeks created so-called water organs of which all parts were already similar to today's instruments. Their creator was an Alexandrian mathematician named Ctesibius (www.organy.net.pl), and a characteristic of this invention was the use of a water tank with a submerged bell which stored compressed air and maintained its constant pressure.

As can be seen in Fig. 1, all pipes stand on the windchest, which is divided into so-called wind chamber (E) and registration compartments (S). Manually driven pumps (F) and (G) pump the air into the bell (C), which is immersed in the water-filled tank (B), (D). Valves are turned on and off with the lever (T). On the left side of Figure 1, on the longitudinal section, a scheme of the mechanism needed to play the instrument is shown. An organist, pressing key (V), by means of a lever mechanism, moves the bar with holes (W) in a position in which the bar's holes align with the holes in the upper side of the windchest. This causes air to flow from the chamber (S) through the pipes. The return of the key to the initial position is realized by spring (X).

In Europe, organs have been built since the mid-fifth century. The size of these instruments increased and the crowning achievement of the first stage of the organ's history was an organ built in 980 in the English Benedictine Abbey in Winchester. This instrument consisted of two keyboards, probably placed opposite each other resulting in the need for two organists.

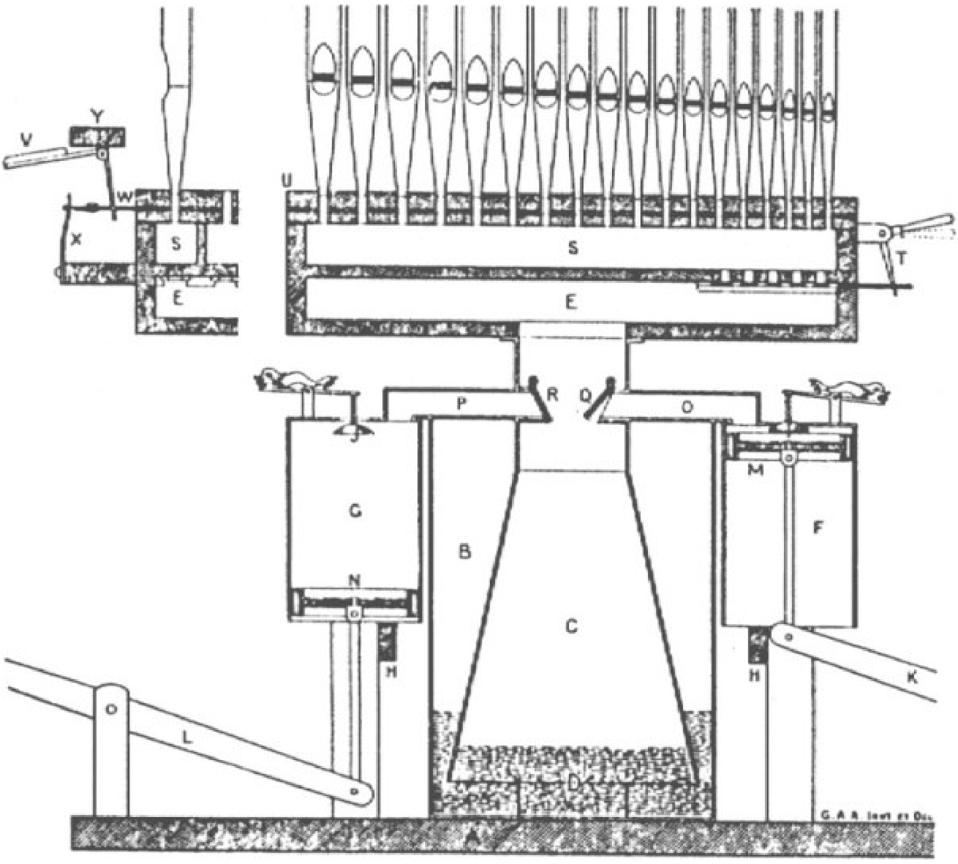

Figure 1. Water organs of Ctesibius – cross section

(source: www.organy.net.pl)

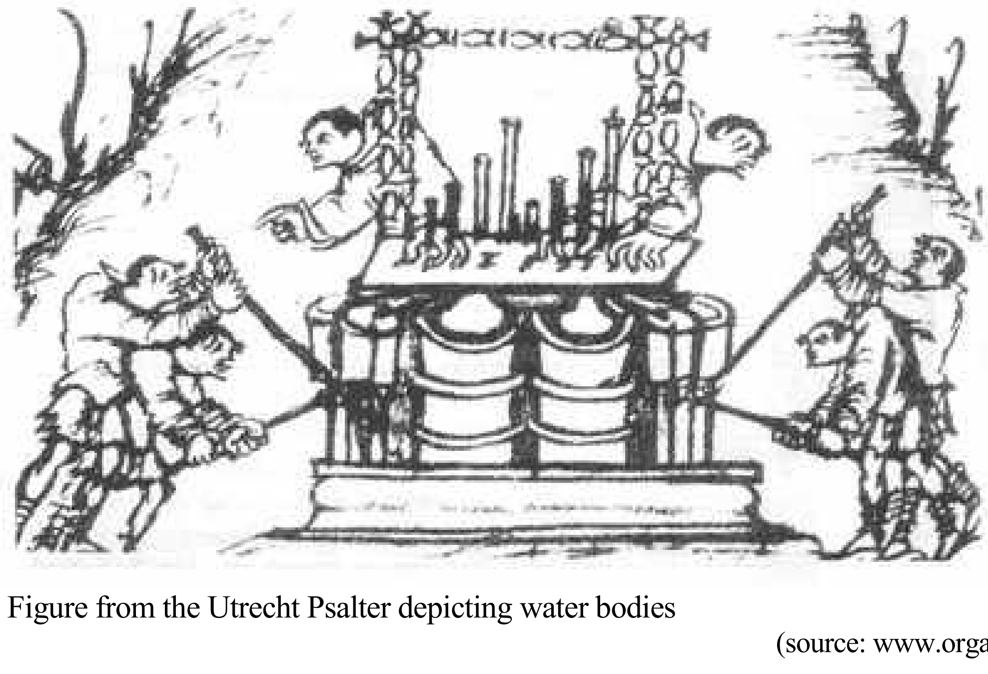

Figure 2. Figure from the Utrecht Psalter depicting water bodies

(source: www.organy.net.pl)

Another example of water organ, on which two organists play simultaneously, are shown in the figure from the Utrecht Psalter (Figure 2). Each of the manuals contained 20 keys, which activated up to 10 pipes at once. Air to the windchests was pumped by 26 bellows. These bellows did not have an expansion tank or any other form of pressure stabilizer, so the fluctuations of the sound amplitude and frequency were quite sudden during the play (Bennett, 2018).

In the following centuries, organs were subjected to other modernizations. However, their development was limited by the use of mechanical action and its complicated structure in larger instruments. This also caused difficulty for the organist by significantly increasing the pressure required on the keys. Only in 1830 did Charles Spackman Barker invent a pneumatic assist device (Figure 3) (Erdman, 1989).

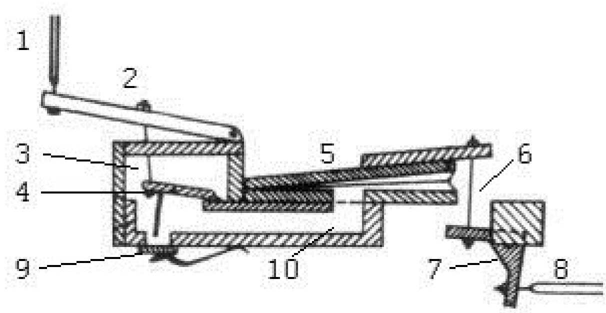

Figure 3. Example of Barker leverage solution

(source: Erdman, 1989)

The organist, pressing the key, carries movement using a tracker (1) on the lever (2) which opens (through the rod (3)) the valve (4). Air enters through it and pushes on the bellow (5) which, through the rod (6), the lever (7), and the tracker (8), opens valves which control air for the pipes. The organist needs only to overcome the resistance caused by the small valve (4). After releasing the pressure on the key, the valve (4) closes up and opens the exhaust valve (9), leading to the chamber (10) and the ambient pressure equalization, so the bellows (5) fall down, and the sound of the pipes fades (Kostek, 1994).

The Barker leverage solution was the first use of pneumatic equipment to support mechanical trackers, which have been replaced by electromagnetic devices in modern day instruments (Erdman, 1989; Kostek, 1994, www.organy.net.pl, www.tomaszmonko.com).

2. Tracker action of pipe organs

There are two separate sets of control mechanisms in pipe organs: the action that controls pipe speech, called a key action, representing a combination of keyboards with windchest valves, keyboard couplers, etc., and stop action, allowing the choice of the sound section of the instrument by selecting the appropriate stops (ranks or sets of pipes), either by hand or with the help of various automated systems, including those with memory (so-called setter memory or combination action) (Bennett, 2018). In principle, it can be visualized that these two sets of controls are perpendicular to each other, as on x / y axes – a key opens the air supply to the windchest channel under all pipes of the same tone (y), and the stop switch allows on its flow from the channels further only to selected stops (x). Thus, only those pipes emit the sound corresponding to the pressed keys and only within the stops that are currently enabled (the Boolean "and" – a logical multiplication function on the two-dimensional matrix).

In the construction of the pipe organ key and stop actions, there are three basic types: mechanical, pneumatic and electrical (or more accurately: electromagnetic) (Flether, Rossing 1998). There also exist solutions with a combination of these types: pneumatic-mechanical, electro-pneumatic, and electromechanical tracker action. Mechanical tracker action is described in Chapter 1, the electric action is presented in Chapter 3.

Pneumatic action involves the use of Pascal's law. Figure 4 shows the use of pneumatic action to control the pipe speech, and Figure 5 – to control the stops. The organist, pressing a key, causes the valve to open, which by means of a tube (1) transports the air to the bellows (2), which act on the tappet to open the valve. Through this valve the air gets into the bellows (3) which open the valve controlling the inflow of air to the terminal with bellows located under the pipes (4) (Figure 5). This solution is dictated by the fact that there are pressure losses in the control system, so the bellows (2) would not be able to open the valve supplying bellows terminal located under the pipes (Bennett, 2018).

In the Figure 4 we can also see bellows (5), on whose cover were three flagstones measuring 50x50 cm and 10 bricks. From this we can conclude that the air pressure in the instrument was quite high for the organs. This was probably dictated by the need to compensate the losses of air which appeared in a control part (tube (1) and bellows (2) in Figure 4 and 5) (Bennett, 2018).

Figure 4. Pneumatic key action in no longer existing organ of St. Roch's Church in Nowy Sącz, Poland, made by the organ-builder Stanisław Aleksander of Rdziostów near Nowy Sącz
1 – supply tube, 2 – tappet-equipped bellows powered by low pressure air, 3 – tappet-equipped bellows powered by higher pressure air, 4 – adjustment screw, 5 – main bellow / tank

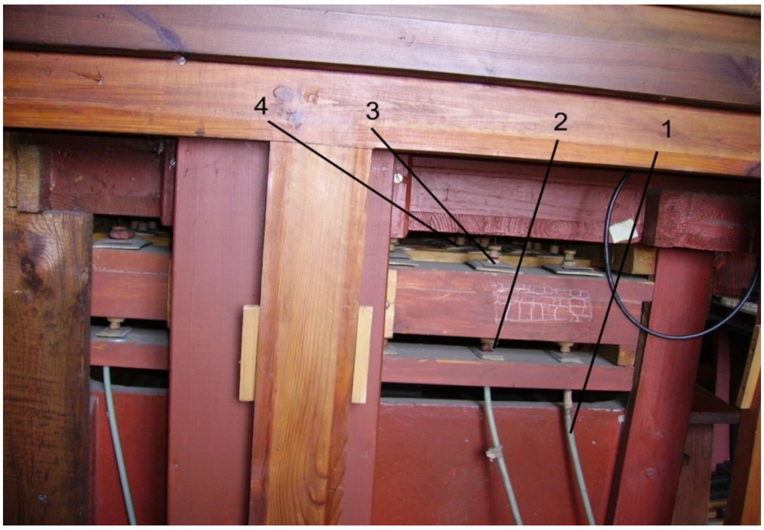

Figure 5. Pneumatic stop action in no longer existing organ of St. Roch's Church in Nowy Sącz made by the organ-builder Stanisław Aleksander of Rdziostów near Nowy Sącz
1 – supply tube, 2 – tappet-equipped bellows powered by low pressure air, 3 – tappet-equipped bellows powered by higher pressure air, 4 – terminal with bellows which control valves opening airflow for the pipes

3. Mechatronic devices used in pipe organs

Mechatronics is an interdisciplinary field of science, the essence of which is the addition of electrical devices to mechanisms in order to improve their operations or obtain the best possible results (Schmid, 2009). Since the invention of electricity, organ builders began to introduce to instruments newer inventions using electricity.

a. compressed air supply

The first such device was electric blower (Figure 6) which eliminated the necessity of tedious work of calcants (bellow operators).

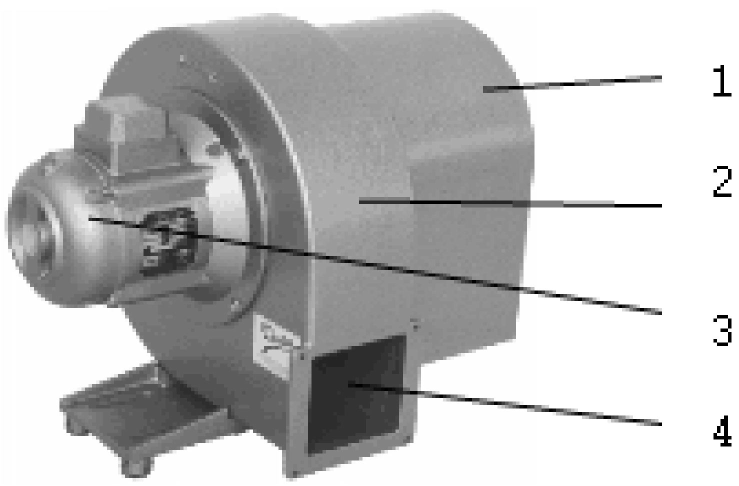

Figure 6. Electric organ blower
1 – Box protecting the inlet of the turbine pump, 2 – blower housing, 3 – electric motor, 4 – outlet
(source: www.organy.net.pl)

Its task is to provide an adequate air compression for the reservoir (main bellow) from which all the receivers in the organs are supplied. The air pressure in windchests is relatively low and normally measures from 295 to 1180 [Pa] (30 to 120 mm of water column). Larger instruments with a specific disposition (for example, those with special high pressure stops) are sometimes equipped with high pressure compressors – from 1960 to 6375 [Pa] (from 200 to 650 mm of water column) (Bennett, 2018). The level of pressure is set once before voicing and tuning of the pipes by placing weights on the lid of the bellows (Figure 7).

Blowers of modern organs (at least the larger ones) are supplied mostly with three-phase electric current. After filling the bellows to the desired state, the "roller blind" suspended on a thread (1) (Figure 7) closes the air supply to the bellows, stabilizing pressure.

To prevent the bellow from exploding in case of failure of the throttle, additional safety valves are mounted. Power of blower motors varies considerably depending on the size of the instruments.

Figure 7. View of the organ bellows
1 – Bracket of the control gear for filling the bellows (throttle), 2 – weights, 3 – blower

An extreme example are the largest pipe organ in the world (Boardwalk Hall Auditorium Organ in Atlantic City, NJ, USA), where this power reaches around 450kW (www.tomaszmonko.com).

All this power is not needed incessantly – if it were, an organist would have to continuously play extended chords using all the stops at once. Most of the time this power is not used, and the blower would still consume a lot of electricity which would be wasted when the throttle is closed. This problem can be solved by varying the blower speed by using a variable frequency driver or by the mechanical drive with the task of adjusting the efficiency of the blower. Control of these devices can be a mechanical switch as a sensor of the bellow's position. This approach requires testing for efficiency of the control system (troublesome when the large inertia of the system could prevent a timely response of the blower driver in the event of sudden changes in demand for air). Currently, the variable frequency drives are used in organ blowers as devices increasing their output in the event of too small size of the turbine (increased frequency of power within the capabilities of the motor – usually not more than 70Hz (for example – organs of the National Philharmonic in Warsaw), as well as to prevent extensive current surges at system start-up – the so-called soft-start (for example – the organ of the Elandstraat church in the Hague).

b. electromagnetic and electropneumatic action

The organ builders' craft almost always draws on the technology from the achievements of other sciences. As a result, in the second half of the nineteenth century, with the development of mechanical and electrical sciences, organs began to be equipped with some of the simplest elements of automation, which are electromagnets. Thanks to them, the design of organs has become very simple compared to earlier solutions – mechanics and pneumatics – and the new electromagnetic action quickly spread around the world. It proved to be an extremely simple solution, in contrast to the complicated connection of trackers, brackets, multiple transmissions in mechanical organs, or unreliable, more complex in structure and failure-prone pneumatic relays and valves.

With the electromagnetic key action, the transmission of signals between the keys and valves of the windchest uses electric cables instead of wooden bands (trackers) or compressed air. This gave the builder huge opportunities in the design of the overall structure of the instrument. The console could stand anywhere, because it no longer had any direct mechanical connection to the rest of the organ. It was not necessary to design and product complex mechanical transmissions. By using much smaller amounts of material, it became possible to build instruments of huge, unprecedented size, especially since – as in the pneumatic action – there was no longer any need for burdening arms and legs of playing person with the extensive force needed to open the valve.

The principle of operation of the electromagnetic key action in conjunction with pallet valves is much simpler than in the case of the mechanical one. It eliminates the use of sets of rollers, brackets and any other transmissions – electromagnets move pallets directly (Figure 8). In conjunction with the windchests that are equipped with conical valves, there is no need to use any form of pneumatic control system between the console and the windchest – likewise, the electromagnet controls the bellow bar directly. This greatly simplifies the entire structure, especially of the console, and gives more flexibility in adding various assistive devices and increasing the number of possible keyboard couplers. This kind of combination of electromagnets with bellow bars of the windchest is known as a electro-pneumatic action.

Since the transmission of signals from the keys is carried here through wiring, construction, equipment and placement of the console is not very important. This has become an extremely convenient solution primarily in concert halls, where the console could henceforth be placed anywhere on the stage, and it could be removed when the concert did not require the organ (Bucur, 2019).

Precision of performance on an electromagnetic instrument is much greater (if it is appropriately adjusted) (Wierzbicki, 1977), the keyboard is light, it can also be adjusted in terms of its resistance, one can easily perform fast note figures, without fear – to such an extent as in the pneumatic key action – that the rows of valves will not manage to provide enough air to the pipes.

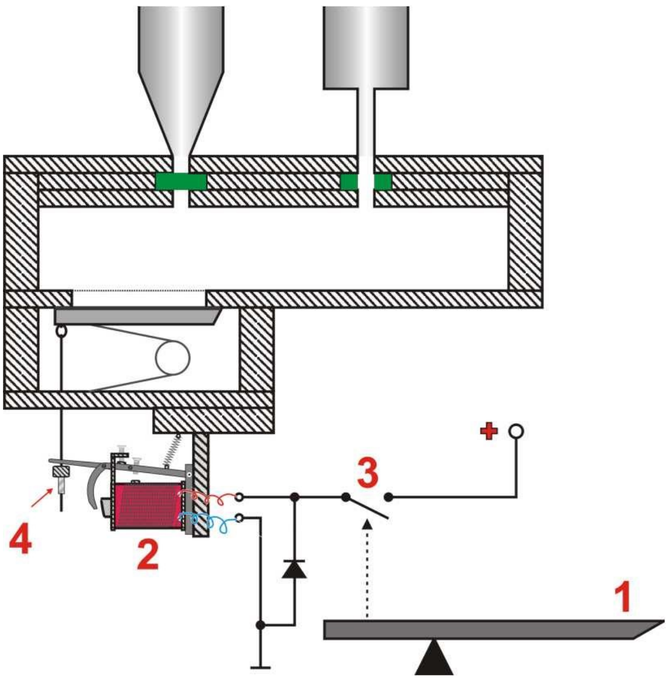

Figure 8. Scheme of electromagnetic key action in conjunction with pallet windchest
1 – key, 2 – electromagnet, 3 – switch, 4 – valve tie bar

Based on the electromagnetic mechanisms, the instrument combines the advantages of mechanical key action (precision) and pneumatic (playability), while not having other main disadvantages: resistance of keyboard and delayed response (Wierzbicki, 1977; Kostek, 1994).

c. accessories – tremulant

In the organs often we can find a device designed to modulate sound, which is called tremulant (Figure 9). The effect is realized by way of a mechanical, cyclic reduction of air pressure in the windchest and back to the initial level.

The whole device is connected by an appropriate channel with the bellows or with a circuit that supplies the windchest locally. Air from the source through the hole (2) fills the box (1). There is a horizontal bellow in the box (3) of which top plate closes the hole (4) in the top part of the box; the top plate of the bellow is of course veneered with sealing material (leather, felt). In this design, there are two tubes supplying air to the bellows that control the valves (6) and (8); inlets of the tubes are located in the small chambers covered by the valves (6) and (7). In the quiescent state (with tremolo effect turned off), the valve (6) is in the lower position. This allows the compressed air from the box (1) to fill the bellows that make the cone float (8). Raised cone opens the inlet to the channel, where the air from the chamber (1) flows into the bellows (3). In this situation, inside and outside of the bellows the air pressure is equal, and the spring (5) presses the upper plate against the wall of the box, closing the outlet (4). While the system is turned on by supplying compressed air through the tube (9), the device – as the result of interaction – oscillates modulating the pressure in the chamber (1).

The tension of the spring (5) can be adjusted by a nut. This changes the amplitude of pressure oscillations in the windchest in a mechanical way, and hence – the range of modulation (Erdman, 1989).

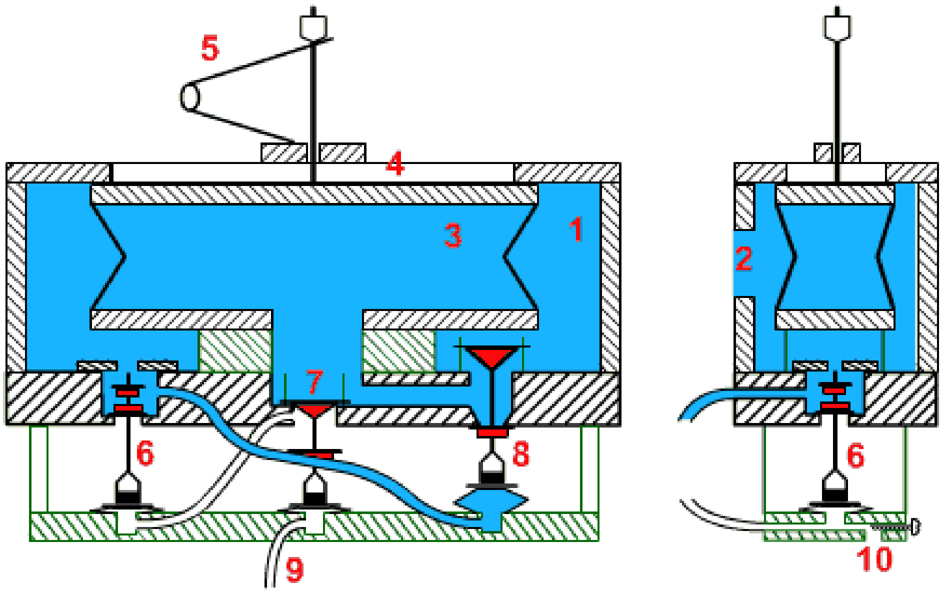

Figure 9. Tremulant operating scheme

(source: www.organy.net.pl)

One of possible constructions of the device allowing setting the sound modulation in an arbitrary manner from the console, is presented in Figure 10. The valve (4) is eccentrically connected to the motor (6), whereby – during operation of the engine – it oscillates alternately, connecting the channels (1) and (2) or (1) and (3). Of course, in moments of transition all channels are connected each together which causes an additional ease effect (shape of the modulating wave).

In the first position, the windchest bellows are connected with the outlet discharging air, which causes a drop in pressure in the windchest. In the second position, the valve (4) connects the bellows to a source of air with a higher pressure than in the windchest, whereby the situation is reversed. It is, on one hand, pushed by the spring, to partially overcome the resistance resulting from the pressure difference between the channels (2) and (3). A second, smaller spring is only to prevent the motor from blocking by the valve abutting the wall.

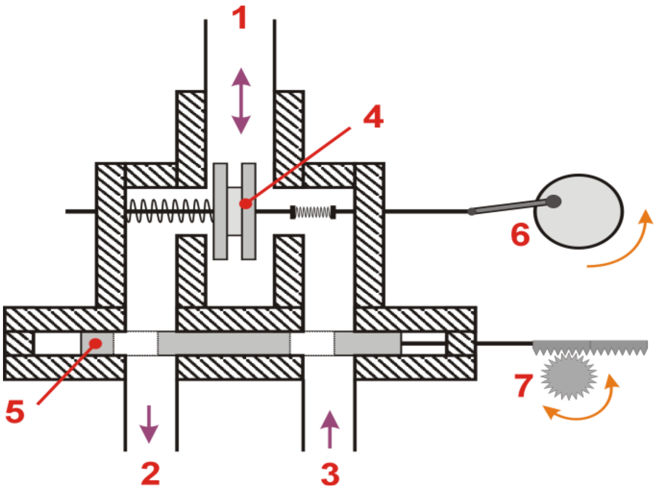

Figure 10. Tremulant construction scheme with adjustable amplitude and frequency
(source: www.t2logic.com)

By changing the motor speed (6), we can adjust the frequency of tremulant operation, for example, by a special potentiometer in the console. There remains, however, no effect on the amplitude of the pressure changes (the faster the vibration of the valve, the less time is for air to flow, so the pressure changes in the windchest are getting faster and smaller), so for its compensation the valve slider (5) is moved by stepper motor (7). To make amplitude independent, at least partially, from the frequency, it expands or reduces both, the inflow and the outflow of air to and from the channel of the bellows (1). This compensation should be performed automatically, after proper adjusting of the control system by the organ builder. It is also possible to adjust the fixed component of the flow by an organist, what results in modification of the tremolo effect amplitude (Kostek, 1999).

d. modern solutions of the tracker action

In the mechanical (tracker) key action, due to the direct connection, the pipe valve moves according to the movement of the key, which gives better control of the articulation and greater possibilities of artistic expression – because it is possible to delicately control the valve opening process which affects, among others, the sound envelope. In the twentieth century, in the construction of larger organs, mainly electromechanical and electropneumatic action was used because of the previously mentioned benefits, such as lack of resistance of keyboard, ease of adjustment, precision of play, and simplicity of design. Currently, however, there is return to a proven solution – mechanical action, though it is often equipped with electromagnetic support devices (Fischer, 2017). These devices, as long as they are based on the use of conventional electromagnets, deprive the artist main advantages of direct mechanics – the control over the pallets opening and shaping the sound by this method. One can not obtain the intermediate position of an electromagnetic valve – it is either open or closed (Knapczyk, 2015) – so in the electromagnetic tracker action the sound becomes somewhat dull, deprived of "soul" while in the mechanical action, aided by electromagnets, the production of sound is fuzzy, as part of the pallet valves work in an "analog" way and other part turns on suddenly, while they all are supposed to move in the same manner (Kostek, 1994).

A revolutionary solution turns out to be equipping the organs in the tracker action which combines the advantages of mechanical solutions (direct sound shaping) and electromagnetic (precision of playing and lightness of the keyboard), while not adopting their disadvantages, such as resistance of keys or "dull" sounding. Such a solution has emerged in recent years and has been launched by the company Syncordia International, but its main drawback is a very large cost, and also the use of relatively non-standard parts. The result of this is – so far – limited implementation of this invention, and it is primarily used only as a device replacing the traditional mechanical between-manuals connection in a few instruments.

A co-author of this study, Tomasz Mońko, in 2005 developed a solution that includes the aforementioned solutions patented by Syncordia International, however, it is much cheaper and could be successfully used in tone windchests. Currently (2016) he is also conducting work on a new, more simply constructed, faster and more energy-efficient version of the system.

In order to develop the basis for the construction of a far more economical to produce, equally functional, reliable type of a tracker action mimicking the movement of a key without relying on a mechanical connection, simpler in construction and self-regulating, he developed the equivalent of the invention of Syncordia: a prototype of electromechanical device designed for transmitting smooth movement of a key to the windchest pallet valve (which is in line with today's trends in the organ construction) (Figure 11). Although, it is referred by the author to as "electromechanical" and "imitational", the solution can be called a mechatronic action.

The principle of operation of this type of key action is this basic concept: the valve in the windchest must be in a strictly predetermined position depending on the level of depression of a key, without being in any way mechanically connected to it. Simply put, one can say that the movement of the key is accurately transmitted to the valve mechanism, despite the absence of a mechanical connection between them.

This is about getting the same effect of playing and sound control as in the mechanical tracker action, although with no need for trackers at all.

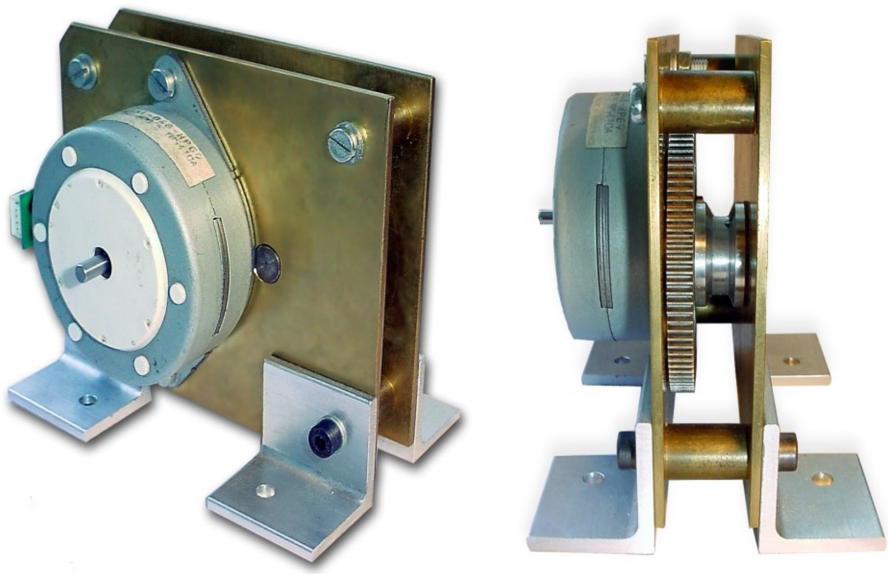

Figure 11. The prototype of stepper-motor module for controlling the valves in the tone windchest

The first version of the prototype involves the use of microcontroller-driven stepper-motor (instead of electromagnets) with transmission (Figure 11). There is a cord, made of a strong material, attached to the wheel (spool), which is mounted eccentrically in order to obtain a non-linear transmission. The other end of the cord is attached to the pallet valve. A 24-volt stepper motor PM55L-048 from eMinebea with a stroke of 7.5° per step, operates at speeds of up to 400 steps per second while maintaining sufficient torque.

The motor gearwheel with 16 teeth moves a bigger, 96-tooth wheel (Figure 11), which is six to one transmission ratio, so the movement resolution also increases sixfold – to 288 steps per revolution of the large wheel, that is 5/4° per a single step. According to calculations carried out by physicist and organist, Colin Pykett, the sufficient time of the tracker repetition is 8 full opening and closing the valve per one second. To ensure compliance with this requirement, the mentioned prototype is able to provide the value of 10 repetitions per second. The stepper motor must be able to fully open and close the valve with frequency of 10Hz, which is very good for playing repetitive notes.

In accordance with this value, the motor speed is set at 400 steps per second, which gives 40 steps for one opening and closing the valve. This implies that the system operating range is 20 steps of the motor (50 ms), what gives angle of 150° rotation of the rotor, or 25° rotation of the large wheel (six to one transmission). The dimensions of the spool wheel attached directly to the larger gear, has been selected to 25° of its rotation and it gives 10 mm of the cord shift. Resolution of the cord motion is determined by the number of steps it takes the motor to open the valve – 20 to 10 mm, so the valve is shifted with an accuracy of 2 positions per millimeter. It is completely sufficient accuracy which allows to specify the output cord movement as smooth, despite of the motor steps. Sampling rate of the key movement by the processor is enormous: more than 100,000 times per second, what – with the entire range of operation (20 possible positions) – makes the certainty of detection very high – to cause a fault, the key would have to be depressed with a frequency of about 2,500 times per second, which is obviously impossible. The motor, however, is limited by the speed of 400 steps per second, and the system has been so calculated to cope with the key repetition to 10 times per second, so with the very unlikely, but possible, exceeding this value, the motor could "lose" steps, entering the erroneous movements, preventing usage of the pallet or even exposing it to risk of damage, as well as the cord or other parts. The software includes a protection against this problem: in the case of any delays in the operation of the motor, the software of the microcontroller prevents false movements by "remembering" number of steps to be executed (the description of the software controlling displacement and managing the motor is in the later part of this chapter) (Kostek, 1999).

Detection of key motion is done electronically using a special dual optocoupler integrated with logic amplifiers (H9720) in which a transparent strip with lines printed on it moves. The strip is attached to the key. The optocoupler detects the movement thanks to the strip which alternately covers photodiodes and exposes them to light. The print density is 150 lines per inch, and there is need for 20 lines, hence the range of strip movement is approximately 3.38 mm. In order to obtain the cord movement by a distance of 10 mm, the strip has to be attached in a specific point of the key to give a ratio of 10:3.38. It is also possible to modify the ratio by changing this attachment point, or by slight change of resolution of strip lines.

The direction of key movement is recognized thanks to the construction of the optocoupler H9720. Actually, these are two optocouplers in a common housing away from each other by a fraction of a millimeter. Each of them works in the same way: it gives voltage signals – 0V when the slot is blocked, and 5V when it is clear. Because of their minimum distance from each other, they respond to the covering with a time shift and because of this the processor (microcontroller) can detect the direction of the movement (Figure 12).

Figure 12. Chart of output states of dual optocoupler during the shifting of the printed lines of the strip in its slot. Left: movement in one direction, right: movement in the other direction. A – output states of one of the photodiodes; B – output states of another. The timing shift shown on both charts results from the geometrical distance between two photodiodes

The whole device is controlled by a microcontroller, and one of its tasks is to count the key shifts with a dual slotted optocoupler, whis is placed in such location that the strip can move freely in its slot. The strip is attached to the key rod (Figure 13).

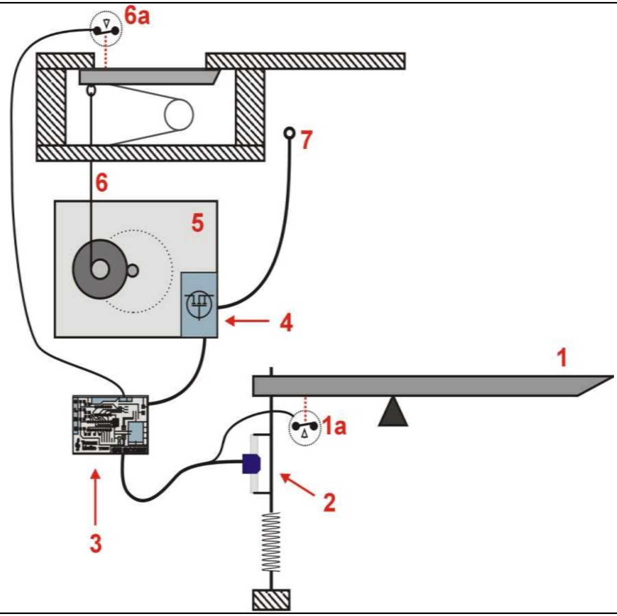

Figure 13. Mechatronic tracker action – schematic diagram

Signals indicating shift of the key 1, reach from the optocoupler (2), by a bundle of wires, to the processor unit (3). Thereafter, the processor converts the signals into pulses for controlling the motor located in the module (5) and with cord (6) the valve is opened in the windchest.

The production cost of the solution shown in Figure 13 is obviously greater than the cost of the electromagnet itself (Figure 8), but in the latter case there is practically no possibility of linear operation. The vulnerability for deregulation of the stepper motor module is surprisingly small. Even possible gradual stretching of the cord (Figure 13) does not affect the operation of the module at all – it is thanks to the well-designed software that enables self-determination of the resting (initial) key and pallet position when the instrument is being turned on. The only problem that can occur is the cord strength, but with today widely used plastics, the module would run for a number of years without failure, which is much longer than even the bellows in the pneumatic action can endure, what – combined with the lack of need for system adjustment – would make the organ almost a "maintenance-free" instrument from the perspective of action maintenance, and thus less costly to operate. Resistance to the broad application of this invention by the organ building companies involves the lack of need for frequent repairs, which deprives them of the income associated with maintenance.

e. stop action improvements

The problem that grew especially from the nineteenth century with the development of organ literature and its requirements in terms of instrumentation, was caused by the necessity of more frequent and more broad registration changes during the performance. This limited both, composers and performers, who sometimes needed several helpers at the console to operate the stop knobs or switches. Brilliant builders, such as Aristide Cavaille-Coll, developed variety of the devices to solve the problem, based on automated pneumatic systems. Thanks to them one could prepare an appropriate registration for use in the later part of the piece before the performance, evoking it in certain moment by just one click. This was the nucleus of so-called combination action – a set of devices that, inter alia, memorize combinations of stops. When electricity became popular for organ builders, the number of possible to prepare memorize combinations triggered by individual keys steadily increased, enabling the performance of works that involved frequent registration changes and eliminating the need to hire helpers. The breakthrough was, however, the fusion of stop action and semiconductors, which gave the opportunity to memorize not a few, but dozens of combinations. Due to the size of today's memory chips, modern systems (called in the Polish jargon "zecer" – from the German "Setzer") can memorize not dozens, but millions of combinations (Bennett, 2018).

In recent solutions a device of this kind can memorize even several millions of combinations. One of the examples is the organ of the Church of St. Casimir in Nowy Sącz built by Werkstätte für Orgelbau Mühleisen from Leonberg near Stuttgart (Figure 14). It is equipped with a memory of capacity of two million combinations.

Figure 14. Console of the organ of the Church of St. Casimir in Nowy Sącz, completed in December 2015

Thanks to the possibilities offered by software, stop action supporting systems are today equipped not only with memory, but also with a number of other features that make performance easier, such as a possibility to preview the memory cell content, disabling specific stops, defining crescendo steps, defining which stops are considered as reeds (French "Anches"), etc. All these functions have been designed and programmed by Tomasz Mońko in the OrgNG system, which is produced by T^2Logic company. This system also controls the key action, allowing the defining a set of programmable couplers that link any division to any keyboard with any semitone offset, exchanging manuals' roles, coupling organs with other MIDI instruments, enabling wireless data transmission between the console and the organ control unit, synchronization of data between multiple consoles, configuration using a touch screen, and many other innovative solutions (Figure 15).

Figure 15. Wireless console, the OrgNG system built by T^2Logic company, the church of St. Andrew Bobola, Gdynia

4. Conclusions

Analyzing pipe organ development in the whole of its history, it can be stated that this instrument passed through a series of upgrades in every epoch, and the art of building has always used current achievements in other fields. With the advent of electricity, organ builders increasingly started to introduce new solutions to organ building, finally replacing the entire mechanical action with electromagnets. For a period of time, they primarily built organs with the electromagnetic action. Only after some time, the problem of so-called "dull" sound has become a cause of appreciation of strictly mechanical solutions, and there has been a resurgence of interest in mechanical tracker action, however this time equipped with variety of supporting devices – electromagnets and further work on improving it is being carried out, like the example presented on Figure 13.

Pipe organ: a musical instrument or a mechatronic device? Given today's achievements in the field of organ building and trends in this field of technology, without a doubt we can say that both of these terms are real and in some ways even inseparable. It seems that without mechatronic solutions, both the construction of the current instruments and the use of them, would be very burdensome. Although classical elements in the construction of organs, such as bellows, windchest, trackers and brackets, are still the foundation of the structure, even if they also evolved and continue to be modernized. Therefore, present-day organ builders use more and more mechatronic solutions in pipe instruments, causing the contemporary organs, especially in the larger sizes, to be complex mechatronic devices.

When using the solutions presented on Figure 13 in organ building, the only mechanical components in the organ's action that will remain are the key (1) with the spring, the cord (6) and the pallet valve. Other mechanical components (trackers, brackets, etc.) will be replaced by mechatronic solutions. In the future, organ building will certainly be increasingly associated with mechatronics, expanding the instrument's sound possibilities and enabling the performance of more demanding works among musical literature.

References

Bennett, W.R. (2018). *The Science of Musical Sound*. Springer Nature Switzerland.

Bucur, V. (2019). *Restoration of Pipe Organs. Handbook of Materials for Wind Musical Instruments*. Springer Nature Switzerland.

Erdman, J. (1989). *Organy, poradnik dla użytkowników*. Warszawa: Wydawnictwo WAW.

Fischer, J.L. (2019). *Shock Wave Characteristics in the Initial Transient of an Organ Pipe*. Springer Nature Switzerland.

Fletcher, N.A., Rossing, T. (1998). Flutes and Flue Organ Pipes. *The Physics of Musical Instruments*. New York: Springer.

Fletcher, N.A., Rossing, T. (1998). Pipe Organs. *The Physics of Musical Instruments*. New York: Springer.

Knapczyk, J. (2015). *Zarys robotyki*. Nowy Sącz: Wydawnictwo Naukowe Państwowej Wyższej Szkoły Zawodowej w Nowym Sączu.

Kostek, B. (1993). Intelligent Control System Implementation to the Pipe Organ Instrument. *Rough Sets, Fuzzy Sets and Knowledge Discovery*. London: Springer.

Kostek, B. (1999). *Control Applications. Soft Computing in Acoustics*. Springer Book Archive.

Schmid, D. et al. (2009). *Mechatronika*. Warszawa: Wydawnictwo REA.

Wierzbicki, A. (1977). *Modele i wrażliwość układów sterowania*. Warszawa: Wydawnictwo WNT.

www.organy.net.pl.

www.tomaszmonko.com.

www.t2logic.com.