AN ORTHOPAEDIC MATTRESS WITH STIFFNESS CONTROL OF PNEUMATIC ELEMENTS

RADEK VOTRUBEC

Technical University of Liberec, Department of Manufacturing Systems and Automation, Liberec, Czech Republic

DOI : 10.17973/MMSJ.2018_03_2017115

e-mail: radek.votrubec@tul.cz

This paper deals with stiffness control of orthopaedic mattresses. There are several pneumatic elements inserted into the body of the mattress. Pressure transducers measure pressure in the elements. Pneumatic valves control input and output air flow. All components including a compressor are inserted in the bed. The initial control algorithm was designed in LabVIEW. The final solution is realized through a microprocessor. It is possible to set the desired stiffness in two zones of the mattress - in the shoulder area and in the hip area. The system has two modes. The desired values can be adjusted manually in order to achieve level position of the spine. In the second case, the stiffness can be changed dynamically and may act against bedsore.

KEYWORDS

vibroisolation, pneumatic systems, pur foam, microprocessor, orthopaedics, sleep quality

1 INTRODUCTION

One of the basic human needs is the necessity of sufficient quality sleep during which the body can regenerate, release stress and gather strength for the day to come. A man spends nearly a third of his life sleeping. A great percentage of people shift the investment associated with high quality sleep to the last ranks of their priority ladder. On the other hand, there have been cases when people bought expensive, multi-layer and multi-zone mattresses regardless what was good for their body shape and parameters. The market with mattresses allowing stiffness control is rather small and focused mainly on manual replacement of the variable parts. It is described in [Jelinek 2017]. Products allowing stiffness control using pressure are rather limited to inflatable mattresses which do not take the body physiology into account. In this case the change of pressure causes the change of hardness of the whole top layer which comes into contact with a person. The mattress described uses an absolutely different principle. In our case the top layer is non-adjustable. The change of pressure in the pneumatic elements changes the shape of the whole mattress which is given by the profile of its base. The goal was to develop a user friendly pneumatic system for fluent control of mattress stiffness in the shoulder and hip areas. It allows the user to set the correct position of the spine, Fig.1. The position in picture A corresponds to too hard a mattress. The body is not sufficiently sunk into the mattress at the shoulder and hip area. Position B corresponds to too soft a mattress. A soft mattress insufficiently supports the body which then forms an arch. Finally, the position in picture C represents a correct body position. The mattress sufficiently supports the body and allows it to sink into the mattress in the shoulder and hip area. We have dealt with similar systems in our department such as controlled stiffness of car seat or other pneumatic systems [Votrubec 2014]. This topic is related to the work on other vibroisolation systems such as an active ambulance stretcher [Votrubec 2011] or a platform stabilized by means of gyroscopes [Votrubec 2013].

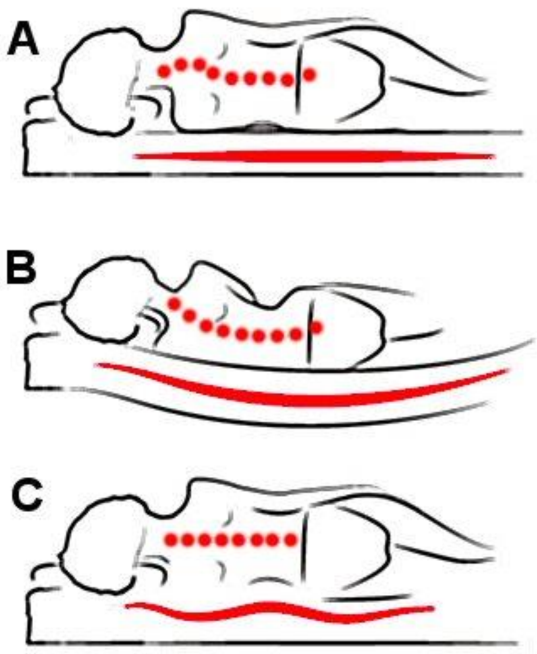

Figure 1. Correct and wrong position of spine

2 DESCRIPTION OF THE MATTRESS

Polyurethane mattresses are the most widespread mattress type. These mattresses consist either of homogeneous foam in the whole volume or of various foam types with different stiffness characteristics. The usable lifetime, i.e. the period of time for which the mattress retains its correct function, usually varies from 4 to 5 years. After such a period the mattress should be replaced.

Another widespread type are inner spring or pocket coil mattresses. These have metal springs or coils in small pockets or rollers between the two bearing layers. Their advantage is longer lifetime (about 10 years) and good permeability. The disadvantage is that these can only be laid on a hard flat surface. Laying them on a slatted base would result in damage to the springs.

The third group are latex mattresses often equipped with a solid coconut core for improved stiffness. Latex is a natural material with excellent point elasticity, antibacterial and anti-allergic properties. The lifetime of latex mattresses is about 7 years. Their disadvantage is high cost.

The last group are lamellar mattresses, Fig. 2 The base of the mattress is made of a wooden lamellar frame (C) supported with three flexible supports made of PUR foam (D) The base is covered from the top with foam or latex bearing layer (B). The whole set is encased in a removable case (A). The supports are offered in several hardness variants depending on the weight of the sleeper. Usually there are four weight categories as shown in tab. 1. In order to optimize the position of the spine during sleep, the supports are equipped with removable inserts (E). These can then be used to adjust the mattress stiffness in individual zones. E.g. in Fig. 2 you can see two zones with reduced stiffness which allow reduction of height at the shoulder and hip area. You can adjust both the stiffness and the width of the zone.

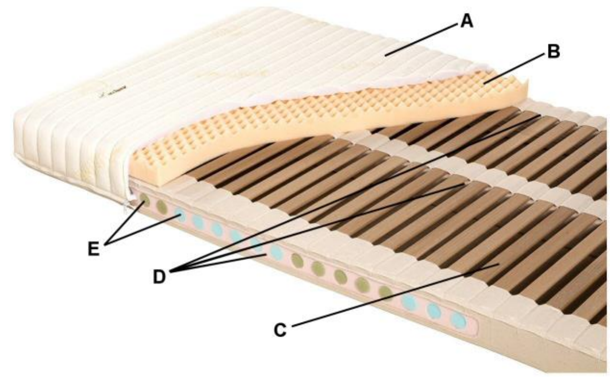

Figure 2. Lamellar base mattress

	support	inserts
up to 60 kg	dark grey	green
60-80kg	blue	dark grey
80-110 kg	pink	blue
Over 110 kg	orange	pink

Table 1. Support variants based on the weight of the sleeper

This mattress type boasts not only best utilities, but also several advantages. They are excellently ventilated and good for asthma and allergy sufferers depending on the used bearing layer They have removable cover and all parts can be replaced. Their lifetime is about 10 years. After this period, it is advisable to replace the PUR foam supports only. The other parts can serve on.

The orthopaedic mattress meets all prerequisites for the requested modification. These namely include the possibility to modify the stiffness control elements. Other advantages comprise removable mattress case and sufficient space to add all components, compressor vents, etc.

3 MATRESS DESIGN WITH ADJUSTABLE STIFFNESS

The aim is to design a possibility to control the stiffness under the following two conditions. First, to extend the scope in which the stiffness can be controlled, i.e. achieve lower stiffness than the **softest** option and concurrently also higher than the stiffest combination. And second, to allow fluent regulation in the whole scope.

Modelling and simulation of the damping force of compressed polyurethane foam is dealt with in art. [Cirkl 2010]. The damping force is described as a function of displacement and velocity (1). These are hysteresis curves. The problem is that it is very difficult to define the α and b_α coefficients analytically. This function can be represented as a function of two variables or its projection to plane F(x). The velocities achieved are small and only a sign can be considered.

$$F(x, x') = b_\alpha x^\alpha x' \qquad (1)$$

The courses of the force produced by the polyurethane foam upon pressing can be measured. A special measuring device was constructed for this purpose. Companies dealing with the development and production of foam rubber products such as mattresses or car seats use an experimental method of pressing in an object whose shape varies depending on the shape and size of the measured foam. There are two basic principles of measuring. In the first one the object is impressed under constant speed and the load value is measured during the whole travel. In the second method the object is impressed with linear force and the depth of impression is measured.

The measuring device has been constructed using ALUFIX modular fixture kit. The mobile part has been designed in a way that allows smooth movement in vertical axis. An element with the dimensions of 100 x 25 mm which is supposed to simulate the base lamella was used as the impressed object, Fig. 3

Figure 3. Foam pressing device with a calibrated tensometer

Fig 4 shows the course of the force during pressing the hardest variant of the support. The blue colour corresponds to the pressing of the support while the red one represents release of the pressure. Fig. 5 shows the course of the force corresponding to the softest variant The measured values for the soft and hard set have served as the reference points for the proposal of optimum scope of adjustable stiffness. The soft variant with the maximum of 33.4 N represents the bottom limit. It constitutes extremely low stiffness which is unlikely to be used in real-life operation, as it corresponds to the softest support and softest insert; the manufacturer does not even offer such a combination. It is therefore not necessary for the proposed bottom pressure limit to exceed this level. In contrast to the above, the values measured for the stiff set with the peak of 61.6 N should be exceeded and the adjustable scope should be set beyond this value.

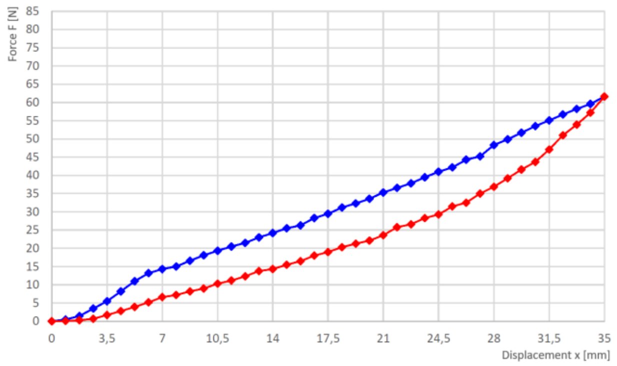

Figure 4. The course of the force when pressing the hardest variant of the PUR foam support.

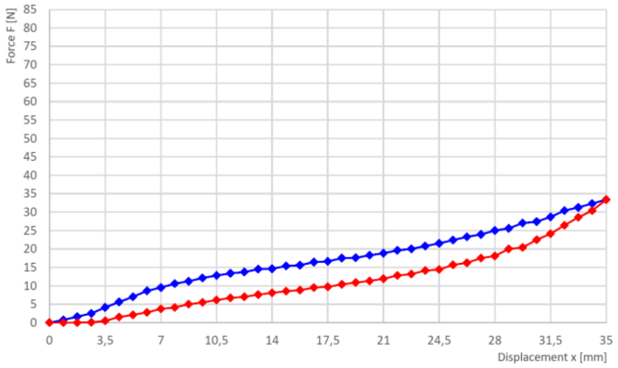

Figure 5. The course of the force when pressing the softest variant of the PUR foam support.

Seven variants were tested when designing the pneumatic element controlling the support stiffness. The variant shown in Fig. 6 was selected as the best one.

Figure 6. Pneumatic element of the mattress

The pneumatic element is made of latex which is best suitable for this purpose. The latex vessel houses the original softest foam rubber insert which ensures a minimum force even with zero pressure. The course of the forces during impression of the support with the pneumatic elements with various pressures is shown in Fig. 7.

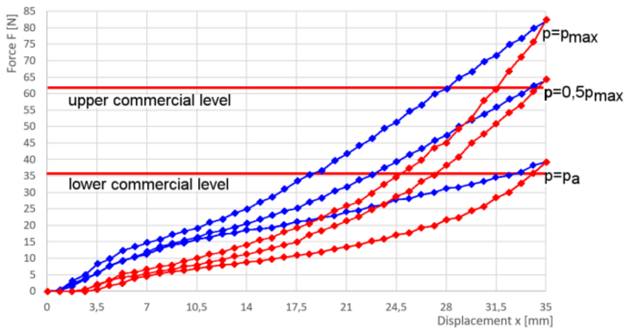

Figure 7. The course of the force when pressing the adjustable variant of the PUR foam support.

The courses of the forces show that the scope of mattress stiffness setting meets the predefined requirements. The lowest adjustable stiffness is on the same level as the softest configuration offered by the manufacturer. The maximum adjustable stiffness is 25% higher than the hardest configuration offered and the mattress can thus be set as extra stiff.

In the first prototype the pneumatic elements were built in the central layer of the mattress only. In the current version the pneumatic elements are in all three supports. This positively influences the correct change of base profile which can then adjust to the body better. The number of pneumatic elements and their position can influence the width and position of both adjustable zones. There is typical configuration of one zone in Fig.8. and there is scheme of two zones of the mattress in Fig.9.

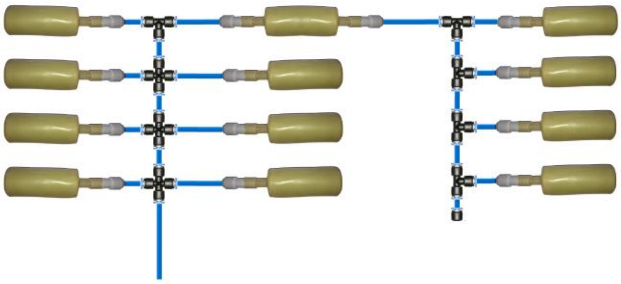

Figure 8. Whole pneumatic zone.

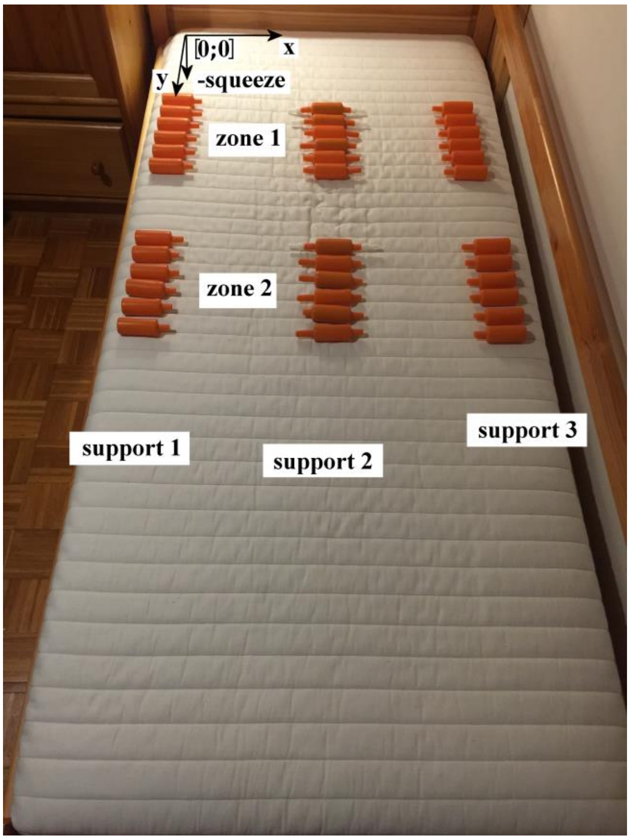

Figure 9. Two zones of the mattress with coordinate system

Method of loading the base with weights has been designed for comparison of support stiffness depending on the pressure. This method monitors the depth of impression or squeeze. It is measured either in one point, e.g. in the centre of the controlled zone –Fig.10, or the weight is gradually moved across the zone and thus the measurement takes place in various parts of the mattress, Fig.11. The weight base has 60 mm in diameter and it weighs 8kg.

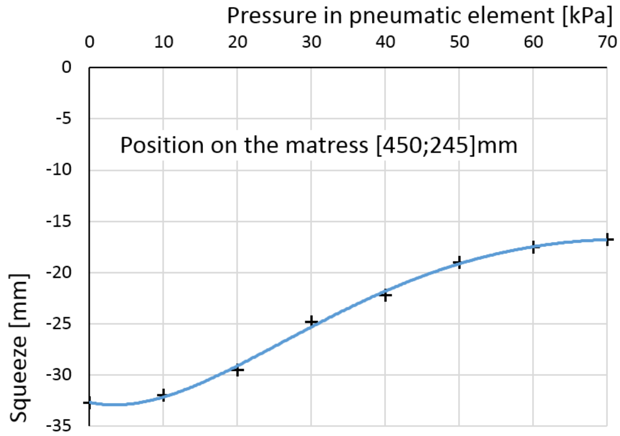

Figure 10. Course of lowering the base depending on pressure.

The pressure adjustment strategy is based on various types of potential customers.

1) Home use - the setting of optimal mattress parameters takes about one month and it is not changed afterwards. Naturally, even in such a case the mattress allows the user to adjust the stiffness according to the current mood or needs.
2) A hotel guest - the mattress parameter setting is based on recommendations arising from the weight of a person with the possibility to adjust the stiffness to lower or higher value.
3) A patient in a hospital with short-term stay - the parameter setting is the same as in the case of a hotel guest.
4) A long-term patient, permanently bedridden - can take advantage of active positioning.

In all cases it is advisable to set the stiffness in individual zones of the mattress in order to achieve the correct position of the spine while lying, Fig. 12

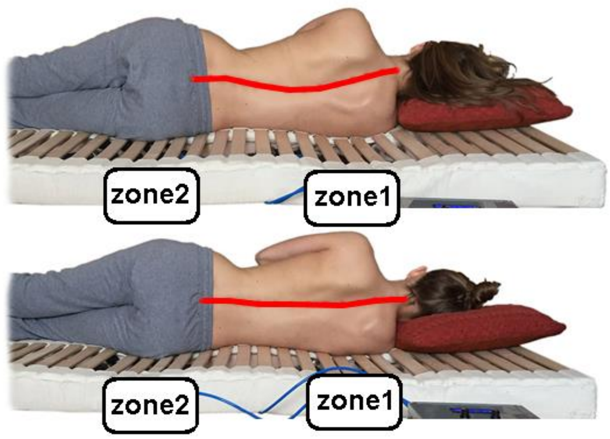

Figure 12. Incorrect and correct setting of the spine position during sleep

4 OTHER COMPONENTS AND THE CONTROL SYSTEM

Air compressor selection is one of the basic issues in the system design. Contradictory requirements for the compactness of the system and reduction of noise which could disturb the sleep pose a problem. The first option is to use a compressor with an air receiver which would be able to cover the need for pressure air during sleep silently and without any problems and the receiver would be replenished in the day or when the mattress is not loaded.

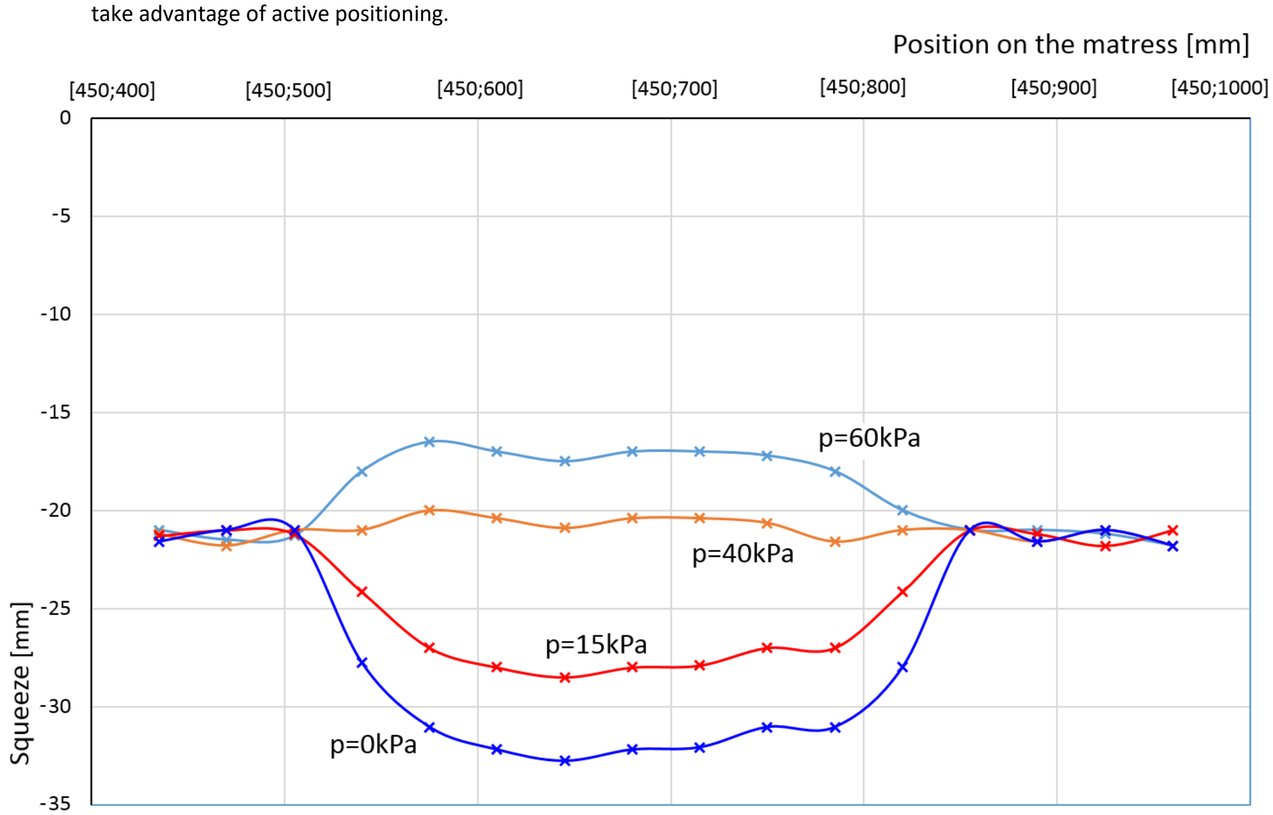

Figure 11. Course of lowering the base depending on the position of the weight for different pressures.

The second option is to use a membrane compressor shown in Fig. 13 This type is used in automotive industry for blowing of lateral seat support bags. Its characteristics include small dimensions, long usable life and most of all, very low noise. The noise level is about 40 dB and it is further reduced by soundproof cloth casing with strong lamination. Moreover, the compressor is stored inside the mattress in a soundproof box under the bearing layer so there is minimal overall disturbance of the sleeping person.

Figure 13. A membrane compressor with a soundproof casing

Other system components are shown in Fig. 14. Besides the compressor they include four pneumatic valves and two pressure transducers measuring the pressure in the pneumatic elements of both zones. All components are connected to Arduino board via magnifiers.

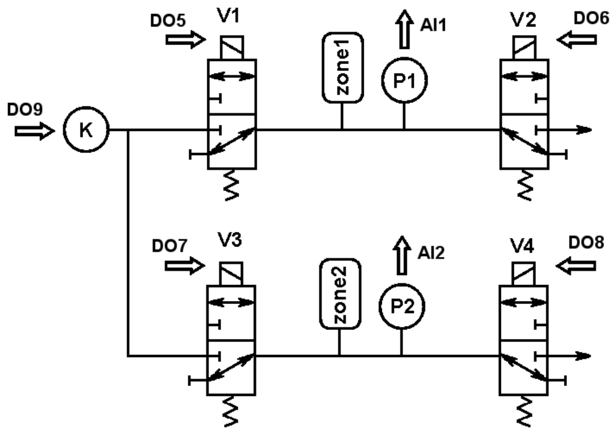

Figure 14. A control system diagram

The control panel is equipped with a display and controls used for parameter setting. Based on the customer types described in the previous chapter, the required pressure is set absolutely using potentiometers z1 and z2 or +/- keys, Fig.15.. It is advisable to use the other keys for setting memory.

There were three ways to control the pressure.

- Analog feedback with PI controller and continuous valves. This method is suitable for dynamic control.
- Combination of continuous analog valves with auxiliary discrete valves, that help to inflate more quickly.
- Finally the third way was chosen because it is the cheapest solution. Only discrete valves are used with two-position control. The pressure is adjusted and then all valves are closed. Dynamic characteristic of initial setting the pressure is in Fig. 16.

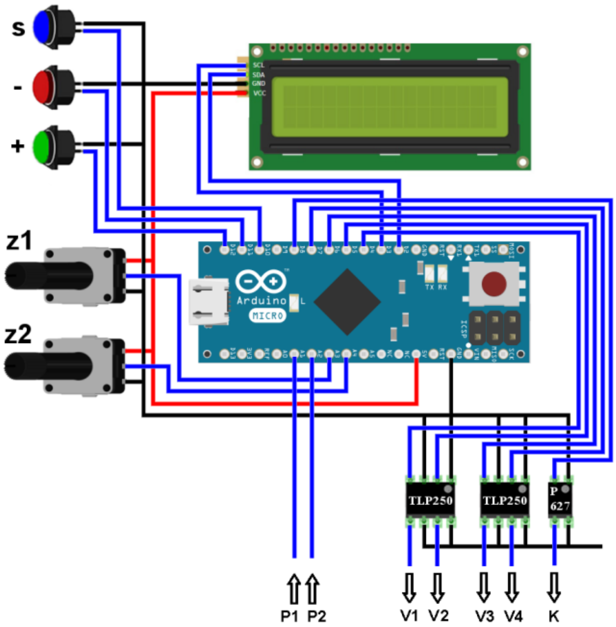

Figure 15. A wiring of control system with Arduino board

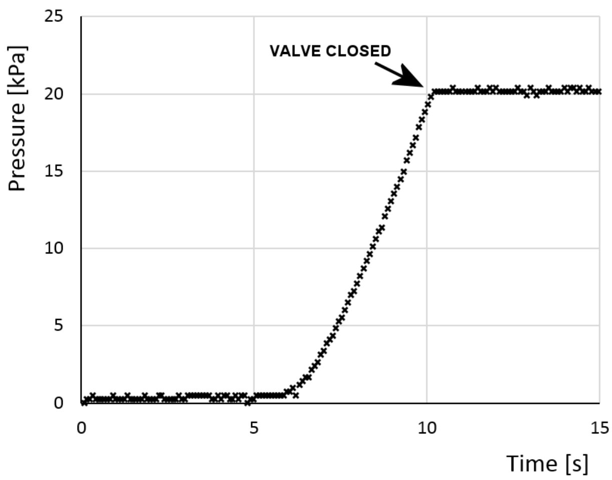

Figure 16. Course of inflating, two-position control, mattress without loading

A photograph of whole control system is in Fig. 17. At this moment all components are in one box. We are going to split the box. Control system part with compressor and valves will be placed into the mattress to reduce noise. Display and controls will stay in smaller external box.

5 CONCLUSIONS

The problem was to design a pneumatic system for stiffness control of the mattress in the shoulder and hip area that would enable setting the correct position of the spine during sleeping in the side position. For all other sleep positions, there is an option to adjust the hardness of the mattress as desired. A prototype of adjustable orthopaedic mattress with variable stiffness was created. Its control system was designed. A control application was programmed in Arduino board. Satisfactory results of control pressure in pneumatic elements were obtained. The adjustable mattress was tested on several people who then assessed the sleep quality improvement. Next it is possible to replace Arduino with a standalone microprocessor board. In the future we are going to design some equipment to measure the spine position. It will enable good setting of pressure in both zones.

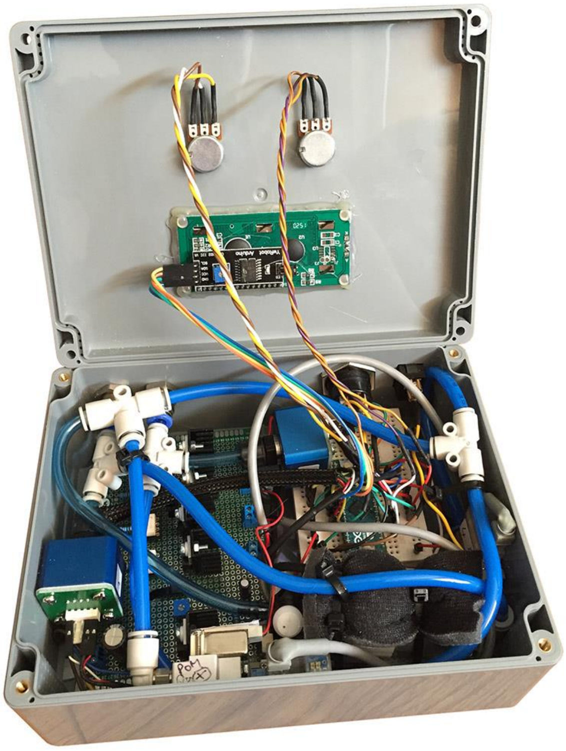

Figure 17. A photograph of whole control system

ACKNOWLEDGMENTS

The research has been supported by project TG01010117 "Proactive system of commercialization at the TUL".

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CONTACT:

Ing. Radek Votrubec Ph.D.
Technical University of Liberec
Department of Manufacturing Systems and Automation
Studentska 2, 461 17, Liberec, Czech Republic
radek.votrubec@seznam.cz