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Magnetic issues of a haptic keyboard

***Abstract**. Haptic keyboards bring the same touch sensation for pianists such acoustic grand pianos. One of the main parts of a haptic device is the actuator, that exerts fairly high and fast changing force. This paper presents the design issues of a voice coil motor type actuator assembly. Magnetic field simulations are carried out to investigate the interaction between actuator units.*

***Streszczenie.** W artykule opisano proces montażu cewki dźwiękowej w siłowniku, na potrzeby keyboardów do tworzenia muzyki z klawiaturami dotykowymi. Na podstawie badań symulacyjnych pola magnetycznego każdego z siłowników, dokonano analizy ich wzajemnego oddziaływania. (**Zagadnienie pola magnetycznego w klawiaturze dotykowej**).*

Keywords: piano action, actuator, magnetic field simulation.
Słowa kluczowe: siłownik, fortepiano, symulacja pola magnetycznego.

IIntroduction

Today the sound produced by digital pianos has gained high standards thanks to the modern synthesis algorithms and signal processing techniques. However the tuch of conventional midi keyboards is far from that of acoustic pianos. In some applications, such as pop music, it is a marginal problem, but interpreting western classical music there is a need to reproduce the same sensation the pianist feels playing an acoustic piano. The reason for this is the fact that sometimes there is more information about an instrument's behaviour through its feel than through its sound. For example to gain the fastest repetition (aftertouch) frequency, the experienced pianist pushes the key by feel again short after detecting the minimum key return necessary to repetition.

To emulate the dynamic behaviour of a real piano action consisting of many levers, springs and masses coupled with changing kinematic constraints supposes two main parts: a motorized keyboard (haptic display device) and a real time signal processing unit. It is clear that such a sophisticated equipment is pretty expensive, but beneficial features such as mobility and changeable touch intensity make it competitive.

The main parts of the haptic display device are the following: traditional key made of wood with ivory coating, sensor to measure key position and/or velocity and/or acceleration, actuator to exert force onto the key as well as signal processing unit. The basic task of the system is exerting mainly acceleration proportional force supplemented with additional forces representing repetition and aftertouch effects. This article deals only with the realization issues of the actuator while system modeling and information processing areas are out of the scope of this paper.

Normally the piano player exerts a force *F(t)* onto the piano key of effective mass *M* that involves the slightly changing inertia effects of the piano action too. The result is the acceleration *a(t)* of the piano key front (Fig.1).

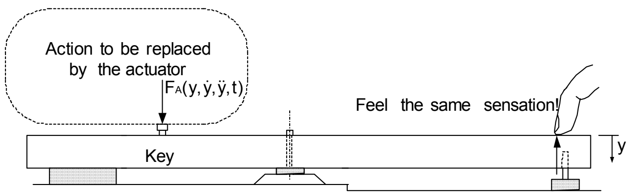

Fig.1. Piano key without action

Changing the complicated piano action of effective mass M with a pure key oh mass m, one has to replace the missing inertia effects by a force F_A=(M-m)a exerted by a suitable actuator to gain the same acceleration. It is to be noted that some relevant effects such as escapement and aftertouch can also be replaced by additional forces. In this case the piano player will not feel any difference between the dynamics of a sophisticated acoustic piano and a haptic display.

According to data found in literature [1,2,3,4] as well as to our measurements on a real piano action the peak reaction force of the action during fortissimo and staccato playing can achieve 50 N, from that about 12 N serves to accelerate the weighed key. As keys of the haptic display are similar to that of acoustic piano, the actuator has to exert about 38 N peak force. The next request is the stroke of the actuator: the distance where the force must be exerted irrespectively of the key position is about 8 mm. The strongest challenge to the actuator is the short duration of force impulse that lasts only some milliseconds at staccato style playing. Consequently there can be taken into account actuators only with small time constant and force free of key position.

Actuator design

The most essential step of actuator design is choosing the right actuator type. Electromagnets, solenoid actuators, magneto-rheological or dry friction brakes and electro-dynamic actuators (DC motors or voice coil motors) can be all taken into account. Even solenoid actuators are widely used in player pianos (Bösendorfer CEUS, Disclavier, PianoDisc) where their role is only to force the hammer to reach the wanted final velocity at a given moment irrespectively of the force-displacement relationships. At haptic keyboards harder requirement takes place, because the force to be exerted by the actuator depends not only on the time but the key position too. Consequently solenoids can not be applied because of their highly nonlinear force-displacement behaviour. Brakes can exert force only to oppose motion thus active force can not be exerted by brakes.

In our work a voice coil motor (VCM) has been chosen and implemented, because only its force was proportional to the input current irrespectively of the key position, as well as its time constant was adequately small. Initially Oboe's work [1] was reproduced, who applied a hard disc drive unit (winchester) integrated with a lever arm as actuator (Fig.2). This design worked functionally well but its peak force was less than needed. The hardest problem with this construction was the lack of enough room at the back of keys. The back of each key measures width of only 14.5

mm therefore conventional HDD units can not be placed in a single line side by side, especially considering the magnetic interaction between them.

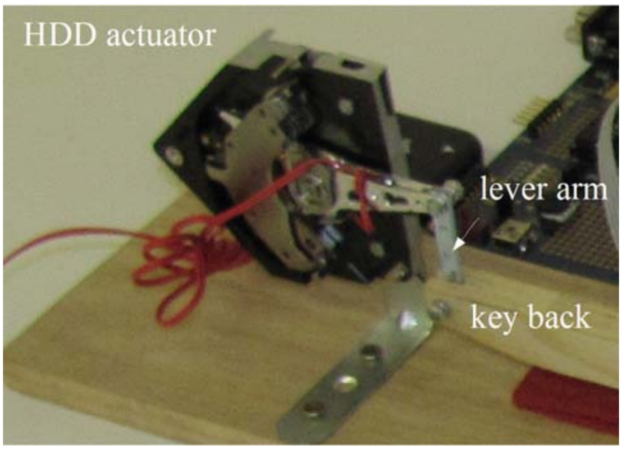

Fig.2. Application of HDD actuator

Preserving the HDD's working principle and its advantages a new VCM prototype actuator has been constructed. Its main feature is the double action of permanent magnets. (Fig.3). As this slim construction makes it possible the in line arrangement of actuator units, each one exerts the same moment onto the keys.

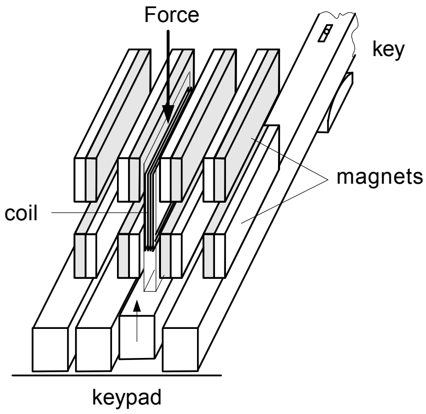

Fig.3. Set up of the magnets

For simplicity the implemented prototype actuator was intended to actuate only one key (Fig.4). Its stationary part consisted of four strong neodymium magnets of width 7mm fixed in a Perspex frame forming an open magnetic circuit The distance of about 7.5 mm between the magnets made is possible to insert a moving coil of width 6 mm. into the gap. The coil was attached to the key back. The effective length of wires in the magnetic field was about 45 mm to obtain as high force as possible.

By our measurements carried out by a KOSHAVA 5 magnetic flux meter the mean value of magnetic flux density was 0.56 T in the gap centre. Magnetic field density distribution was simulated as well as visualised by means of magnetorheological fluid LD 132 (Fig.5 and 6)

Force measurement was also carried out to check the performance of the actuator. Peak force about 12N was reached at an input voltage step of 6 V. The magnitude of force can be increased for a short time using higher input voltage without the danger of overheating.

Even force measurements proved the applicability of the first single actuator unit, it gave not satisfactory information on the magnetic properties of a real keyboard of eighty-eight keys. It was namely not known the extent of the interaction of magnetic fields of the individual actuator units placed closely side by side. The main benefit of our intended fashion is the double utilization of magnets. Each magnet takes part in generation of the magnetic field of two adjacent actuators. This slim construction would allow placing 88 units side by side in the available room.

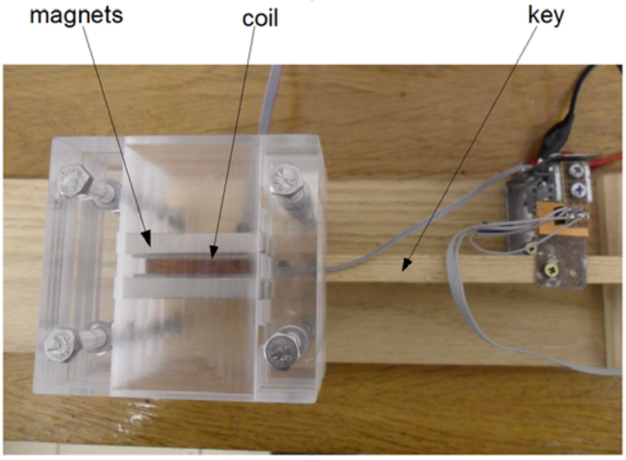

Fig.4. Top view of the prototype actuator

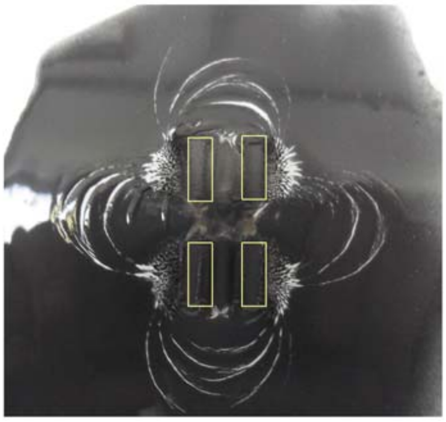

Fig.5. Magnetic flux lines visualised by MRF

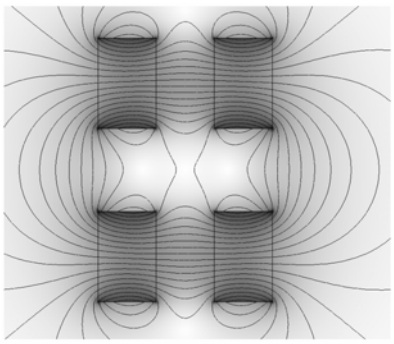

Fig.6. Magnetic flux lines by simulation

Simulations

To find out the magnetic performance of the real keyboard, numerical simulations were carried out using COMSOL simulation software. During the analysis the magnetic flux density distributions in the gaps were studied at different kind of magnet arrangements. For simplicity 3 adjacent gaps were studied.

First the magnetic interaction of neighbouring VCM's was investigated without flux guides between units (Fig.7).

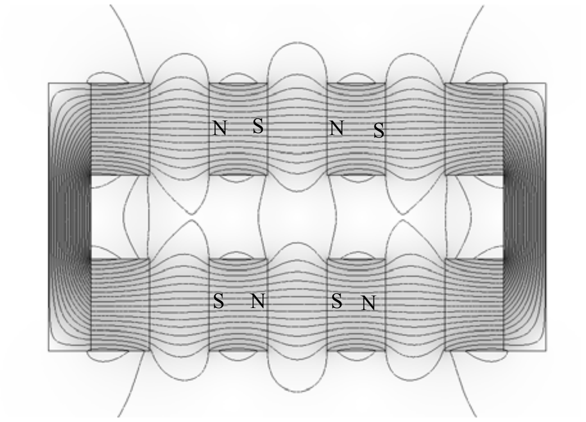

Fig.7. Magnetic flux lines without flux guides between units

After this simulation the effect of intermediate flux guides was investigated. The reason for this was to make the magnetic circuit closed as many as possible and lessen the width of magnets. Two set ups were investigated: one with N-S-N-S…polarization and one with N-N-S-S-…. arrangement. The results can be seen in Fig.8 and 9.

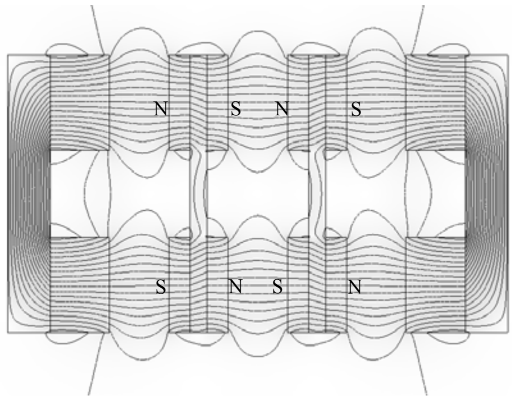

Fig.8. . Magnetic flux lines applying intermediate flux guides, N-S-N-S set up

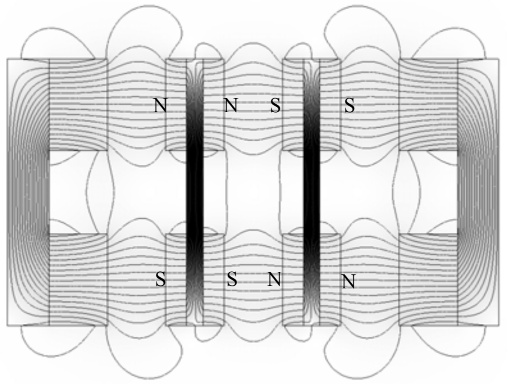

Fig.9. Magnetic flux lines applying intermediate flux guides, N-N-S-S set up

Results of simulations

The result of our findings can be seen in Fig. 10. The highest magnitude of magnetic flux density (B=0,56 T) was found without internal flux guides. The worst result was gained in the presence of internal flux guides in N-N-S-S-set up. The distribution of magnetic field density was not fully homogenous: at the edges of the gap we found 0,37 T, and in the middle 0,56T.

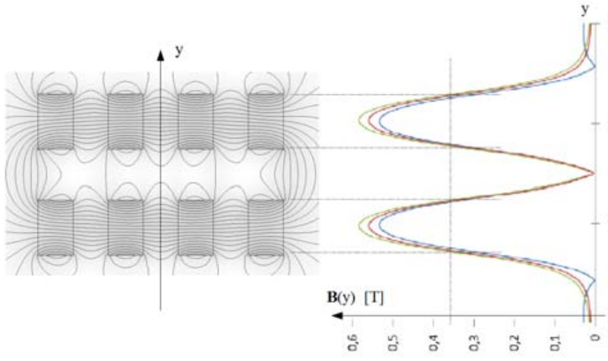

Fig.10. Magnetic flux density distribution in the middle gap.

Conclusions

In this paper some design issues of a voice coil motor array, intended as the actuator of a haptic keyboard was presented. This haptic keyboard can mimic all the dynamic features of an acoustic piano providing the same feel and sensation to the pianist. The unique feature of this actuator array is its open magnetic circuit consisting of double-operation magnets that allow a compact structure. Magnetic field simulations proved that in this open circuit the average magnetic flux density of each actuator unit is nearly the same and does not occur interaction among them. Both magnitude and speed of force exerted by this actuator is proper for the intended application.

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