ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

# FORCE TRANSDUCER PIANO KEYS AS AN INNOVATIVE APPROACH FOR PIANO PEDAGOGY

**Ph.D. THESIS**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

# PİYANO EĞİTİMİ İÇİN YENİLİKÇİ BİR YAKLAŞIM OLARAK KUVVET ALGILAYICISINA DÖNÜŞTÜRÜLMÜŞ PİYANO TUŞLARI

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**HAZİRAN 2022**

Asaf Çetin Eren, a Ph.D. student of ITU Graduate School student ID 409132005 successfully defended the dissertation entitled "FORCE TRANSDUCER PIANO KEYS AS AN INNOVATIVE APPROACH FOR PIANO PEDAGOGY", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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*__To my country,__*

## FOREWORD

This thesis, titled "Force Transducer Piano Keys As An Innovative Approach For Piano Education", is submitted for the degree of Doctor of Philosophy at the I.T.U. Social Sciences Institute, Dr. Erol Üçer Center for Advanced Studies in Music (MIAM).

It is my pleasure to acknowledge the roles of several individuals who were instrumental for completion of this Ph.D. research.

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March 2022

Asaf Çetin EREN
(Pianist)

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## ABBREVIATIONS

| | |
|---|---|
| **3D** | : Three Dimentional |
| **ADC** | : Analogue to Digital Converter |
| **ANOVA** | : Analysis of Varience |
| **BPM** | : Beats Per Minute |
| **CAD** | : Computer Aided Design |
| **CNC** | : Computer Numerical Control |
| **DAW** | : Digital Audio Workstation |
| **Disp-** | : Displacement Sensor Number |
| **DOF** | : Degree of Freedom |
| **EEG** | : Electroencephalography |
| **EMG** | : Electromyography |
| **FEA** | : Finite Elements Analysis |
| **fMRI** | : Functional Magnetic Resonance Imaging |
| **FOV** | : Field Of View |
| **ICA** | : Independent Component Analysis |
| **MEG** | : Magnetoencephalography |
| **MIDI** | : Musical Instruments Digital Interface |
| **mm** | : Millimeter |
| **MoCap** | : Motion Capture |
| **n.d.** | : no date |
| **NIRS** | : Near Infrared Spectroscopy |
| **Op.** | : Opus, (Work Number) |
| **PET** | : Positron Emission Tomography |

## SYMBOLS

| | |
|---|---|
| A | : Cross-Section Area |
| $\mathbf{A}_{[nxp]}$ | : Force-Stain Transformation Matrix |
| b | : Width of The Beam |
| c | : Distance From Beam Longitudinal Axis to Top/Bottom Surface |
| E | : Young’s Modulus (Modulus of Elasticity) of The Beam Material |
| $\varepsilon$ | : The Axial Strain Values Read From Strain-Gauges |
| $\mu\varepsilon$ | : Microstrain |
| $\boldsymbol{\varepsilon}_{[nx1]}$ | : Vector That Contains Strain Values at n Points |
| $\varepsilon_{xx}$, $\varepsilon_{yy}$, $\varepsilon_{xy}$ | : Strain Components in Local Planar Coordinates |
| F | : Vertical Load |
| $\mathbf{f}_{[px1]}$ | : Vector That Force Values Effecting The Object at p Points |
| h | : Height of The Beam |
| I | : Moment of Inertia |
| K | : Proportionality Coefficient of a Strain-Gauge (Called The Gauge Factor) |
| L | : Distance of Point of Force Application to The Strain-Gauge |
| M | : Moment (Bending) |
| N | : Normal Load (Pushing The Keys Towards or Pulling It Backwards) |
| R | : Resistance of Gage |
| $R_{YS}$, $R_{NS}$, $R_{YH,}$ $R_{NH}$ | : Support Reactions |
| U | : Supply Voltage |
| Y | : Lateral Load (Pushing The Keys to Left/Right from The Viewpoint of The Player) |
| ρ | : Specific Resistance (Material Property) of The Wire Material |
| X | : Coordinate (mainly in axial direction of key) |

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# FORCE TRANSDUCER PIANO KEYS AS AN INNOVATIVE APPROACH FOR PIANO PEDAGOGY

## SUMMARY

This study aims to reveal the necessity of new approaches in piano education and to present an innovative technology that can be applied in this direction.

According to Newton's impulse-reaction principle, everything that the pianist feels in her/his fingertip while playing the piano is reflected on the piano key side in the same way. Although pianists and piano educators find it difficult to put these feelings into words, piano keys can transform these reflected feelings into data through the right sensor design. Measuring the forces applied to the piano keys can objectively examine many arguments for better piano playing.

Within the scope of this thesis, piano keys are converted into force transducers. The method behind transforming a piano key into a force transducer is that attaching sensors called strain-gauges to the points of the piano key determined as a result of calculations, with specified angles. Strain-gauges are extremely sensitive to changes in length on the surface to which they are attached. They create circuits that produces voltage changes. Via these voltage change values, the amount of straining (mainly due to bending) at certain points of the piano key can be observed and recorded. This way, the forces applied to piano key can be evaluated.

Due to the data gathered from the tests with the force transducer piano key, temporal variations of keys's displacements and strain values on keys with various types of playings such as *forte staccato*, *forte legato* and *piano legato* are obtained. It is observed that the force is applied for a shorter time in *staccato* and longer in *legato*. In *piano* and *forte* playing, the difference in the slope of the time-displacement curve is detected. In *piano* playing, less strain on the tip of the key is detected. With the data collected from a trill (a musical ornament consisting of a rapid alternation between two adjacent notes) played with different techniques, the change in technique is reflected in the recorded data. Successive transients in the piano key and the mechanism when the key is pressed and the different stages of the mechanism's operation can be observed in the graphics.

This system, which is created within the scope of this thesis, can be applied to adjacent keys, succeeds in providing an process that is not different from an ordinary piano experience visually or tactilely to the pianist and is able to produce sensitive and reliable data. With further improvements to be implemented on this new, patent-pending system, the proposed methodology can play an important role in re-defining piano pedagogy.

**PİYANO EĞİTİMİ İÇİN YENİLİKÇİ BİR YAKLAŞIM OLARAK KUVVET ALGILAYICISINA DÖNÜŞTÜRÜLMÜŞ PİYANO TUŞLARI**

# ÖZET

Bu çalışma, piyano eğitiminde yeni yaklaşımların gerekliliğini ortaya koyma ve bu doğrultuda yenilikçi bir teknoloji sunma amacı taşır. Piyano, çoğu çalgıya göre çok yer kaplayan, pahalı, zor taşınır ve görece ileri seviyede çalınabilmesi için çok emek isteyen bir müzik aleti olmasına rağmen, dünyada, en yaygın kullanılan ve eğitimi en çok talep edilen enstrümanların başındadır. Başta daha çok Avrupa üst sınıfına ait olmuş sonradan tüm insanlık için popülerleşmiş bu çalgı, bu talebe tezat oluşturacak şekilde, tarih boyunca, icrasını zorlaştıracak nitelikler kazanarak evrimleşmiştir. Bu zorluklara rağmen, virtüöz diye adlandırılan piyanistler her zaman varolmuşlardır ve bu virtüözlerin hakimiyetlerinin altında yatan sır, geleneksel piyano eğitimi dahilinde açığa kavuşturulamamıştır.

Daha iyi piyano çalabilmek vazgeçilmez bir hedef olarak hep süregelmiştir. Bu doğrultuda her türlü fırsattan istifade edilmeye çalışılmıştır. Kayıt teknolojilerinin imkanlarından sonuna kadar faydalanılmış, tekrar kayıt, kesme, birleştirme imkanları sayesinde gerçek üstü nitelikte performans kayıtları üretilebilmiştir. Bedene, güç, esneklik, dayanıklılık gibi katkılar sağlama amacıyla spor aletlerine benzer aletler üretilmiş ve sakatlanma olasılıkları artsa da düzenli piyano çalışmalarına bu aletlerle çalışmalar da eklenmiştir. İmkanı olan piyanistler, icracılıklarına avantaj sağlamak adına, piyanolarına özel ayarlar yaptırmışlar hatta bu doğrultuda özel piyanolar bile ürettirmişlerdir. Tüm bu ve benzer sayısız çaba, daha iyi diye kabul edilen bir müzikal ideale ulaşılamamış olunma ve bu durum beraberinde doğan ihtiyacı giderme doğrultusunda ortaya çıkmıştır.

Piyano tekniği, piyanistin, uygulayacağı kuvvetler, yapacağı hareketler ve bu esnada uzuvlarının alacağı postürler olarak tanımlanabilir. Piyano çalarken, amaçlanan hıza, dayanıklılığa, tuşeye vb. ulaşılamamasının sebebi, o nitelikteki performansı sağlayacak hareketlerin, postürlerin, kuvvetlerin kullanılmaması olabilir. Fakat, kullanılan tekniğin, hedefe ulaştırıp ulaştıramayacağı noktasında çelişkili bir bilinmezlik mevcuttur. Hedefe ulaşılamama sebebinin, kullanılan tekniğin yanlış olması mı yoksa o tekniğin yeteri kadar tekrar edilip alışkanlık haline getirilememiş olması mı olduğu genelde bilinemez. Diğer yandan, hedeflenen bir icrayı gerçekleştirebilmek için birden fazla farklı teknik de geçerli olabilir. Tüm bu kapsamda, daha iyi çalanların, neden daha iyi çaldığına dair hareketler ve postürler bazında tarih boyunca bir çok farklı fikir beyan edilmiştir. Bu farklı fikirler bir kaç ana başlık altında toplanabilirler. İlk önce piyanonun atası denebilecek çalgı olan harpsikordun geleneğinden gelen, yoğun bir şekilde parmak kullanımının terbiye edildiği, vücudun diğer bölgelerini sabit yani bir anlamda etkisiz kılan parmak tekniği ekolü baskın bir şekilde var olmuştur. Sonrasında, parmak tekniği ekolüne bir tepki olan, değişen müzik anlayışıyla ve evrilen piyano mekaniğiyle uyumlu, kol ağırlığı tekniği veya diğer bir adıyla fizyo-anatomik ekol etkili olmuştur. Fizyo-anatomik ekolün bir kolu, ileri seviyeye gelmiş piyanistlerin kendi tecrübelerine ve

gözlemlerine dayanan, öznel argümanlar üretirken, daha sonraki ayrı bir kolundaki yazarlar, ileri seviyede piyanistlik veya piyano öğretmenliği tecrübelerinin olmamasının getirdiği zaaflara rağmen, nesnel deneyler yaparak çok önemli bir yaklaşım gerçekleştirmişlerdir. Kronolojik olarak daha sonra ortaya çıkan ve zihinsel çalışmayı ön plana çıkartan ekol, önceki ekollerin yoğun egzersiz programını ve anatomi kurallarının ortaya konulup bunların hesaplanarak çalışılmasını reddetmiş, hedeflenen müziği, müzikal imgeyi odağa yerleştirmiştir. Mental-psikolojik ekol diye adlandırılan bu yaklaşımın iddiası, müzikal imgenin yeteri kadar net olmasının, bedeni, o imgeye ulaşmak için en doğru tekniğin sezgisel olarak uygulanmasına iteceğidir. Zihinsel farkındalığı ön plana çıkartan bu yaklaşımın da kendi içinde, esere çalışma olarak uygulanacak yapısal değişiklikler kurgulamaktan, piyanoya hiç dokunmadan tamamen zihinde müziği düşünerek çalışmaya bir çok farklı alt yaklaşımı da mevcuttur. Tüm bu fikirlerin çeşitli şartlar altında farklı oranlarda doğruluk payları vardır. Bu tez, bu oranların tespiti için nesnel bir ölçüm yöntemi öne sürme gayesindedir.

İcadından bu yana, piyanoyu daha iyi çalabilmek için hangi tekniklerle çalışılması gerektiğine dair bitmeyen iddialar öne sürülse de gelişen teknolojinin sağladığı imkanlar doğrultusunda yapılandırılmış bir piyano pedagojisi gelişememiştir. Bu durumun temelinde bazı zorluklar ve dirençler mevcuttur. Piyanistlik kariyerde rekabet çok serttir. Bu doğrultuda, diğer disiplinlerden de beslenme bir kenara bırakılarak, tüm zaman, piyanistlikte uzmanlaşmaya adanır. Temel bilimlerin yanı sıra, bestecilik, doğaçlama, akort, reglaj gibi piyanistlikle çok daha yakın alakalı olan bir çok bilgi ve becerinin öğreniminden de feragat edilmiştir. Piyano tekniği tarihine, piyano mekaniğine ve insan bedenini incelemeye ciddi bir emek ayırılmaz. Diğer bir yandan, gerek piyanistlerin gerek piyano öğretmenlerinin büyük bir kısmı, piyanistik becerilerinin temellerini çocukluk dönemlerinde başlayan eğitimlerinde atarlar. Bu becerilerin aktarımı büyük ölçüde, küçük yaşta bir öğrencinin fark etmeden öğretmenini taklit etmesiyle olur. Bu durum bazı öğrenciler için faydalı olabilse de ihtiyacı olan bilgiyi alamayıp piyanoyu bırakan bir çok öğrenci vardır. Hatta, bir çok piyano eğitmeni, alışılmış eğitim metotları dolayısıyla yetişen piyanist sayısını yeterli bulup, piyanoda yeni bir eğitim yaklaşımının denenmesini gereksiz bulmaktadır. Bazıları da analitik düşünmenin, sanatsal yaratıcılığı zayıflatacağını savunur. Tüm bunların dışında, piyanistlikteki yoğun rekabetçi ortamda, kullanılan parmak numaralarından oturma yüksekliğine kadar bir çok detayın, meslek sırrı olarak saklı tutulup paylaşılmama eğilimi de tarih boyunca mevcuttur. Her şeyin ötesinde, faydalı olacak bir piyanistik bilgi aktarılmak istendiği takdirde de bu sefer dilin kısıtları aktarımı zorlaştırmaktadır. Piyanistin veya piyano öğretmeninin bedeninde hissettiği ve talebeye aktarmak istediği hissi, kelimelere dökmesi oldukça zordur. Kullanılan, gevşek, serbest, hafif, sıkı, sert vb. kelimelerin, insandan insana farklı algılanma olasılığı ise süreci iyice zorlaştırır. Piyano deneyiminin kelimelere dökülmesindeki bu zorluk, özellikle fizyo-anatomik ekol dahilinde yazılmış bazı yayınların tekrar düzenlenmiş açıklamalarının, aynı yazar veya yazarın öğrencileri tarafından sonradan yayınlanma gerekliliğine sebep olmuştur. Ayrıca, daha iyi piyano çalmak için ortaya konan eski önermelerin, zamanla teknik olarak değişime uğramış bugünkü piyano üzerindeki geçerliliğine şüphe ile yaklaşılmalıdır. Tüm bu faktörler, gelişen teknolojinin imkanlarını kullanan yeni bir piyano eğitim yaklaşımına olan ihtiyacı ortaya koyarlar.

Teknolojik gelişmelerden faydalanarak, kantitatif deneyler tasarlanmış ve nasıl daha iyi piyano çalınacağına dair çalışmalar yapılmıştır. Bu çalışmalarda analizi yapılan veriler başlıca, hareket yakalama, elektromiyografi, elektroensefalografi, MIDI (musical instruments dijital interface) vb. kaynaklıdır. Bunlar dışında, piyanonun, mekanizmasının çalışmasının ve ses tahtasının salınımlarının sanal modellemesini hedeflemiş çalışmalar yapılmıştır. Ayrıca daha gerçekçi dijital piyanolar yapabilmek adına, akustik piyanodan piyaniste geri gelen titreşimleri dijital piyanoda yaratmaya yönelik akademik çalışmalar da mevcuttur. Piyano alanında yapılan kantitatif çalışmalar piyano üzerinde kalmakta yetinmemiş, piyanistlerin parmaklarının ölçüleri, esneklikleri gibi biyomekanik veriler üzerinde de çalışılmıştır. Ne yazık ki, bu yaklaşım piyano eğitimi içerisinde hak ettiği yeri bulamamış ve genellikle tıp ile mühendislik akademik çevrelerinde sınırlı kalmıştır.

Yapılan kantitatif çalışmalarda sıklıkla karşılaşılabilen durumlardan biri, kıyaslanan iki piyanist grubunun, belirli bir teknik beceriye sahip olanlar veya olamayanlar olarak değil de, deneyimliler-yeni başlayanlar, yarışma kazanmış olanlar-olmayanlar şeklinde kurgulanmış olmasıdır. Büyük virtüözlerin bile belirli noktalarda tekniklerinin birbirlerinden daha üstün olduğu düşünülürse, kıdem veya konum üzerinden değerlendirme yerine, doğrudan, seçilecek belirli teknik beceri üzerinden denekleri iki gruba ayırmanın daha anlamlı sonuçlar vermesi beklenir. Yapılan kantitatif çalışmalara dair başka bir durum da, yapılan çalışmaların bir kısmının piyanistlerle ortak çalışma şeklinde olmadan sadece tıp doktorları, mühendisler ve/veya teknisyenler tarafından yürütülmüş olmasıdır. Çalışmalarda yer alan uzmanların büyük çoğunluğu ileri seviyede piyano çalma tecrübesine sahip olmadıkları için sınadıkları hipotezler piyanoda başlangıç seviyesi kapsamında olabilmektedir. Ayrıca, piyanodan veri toplamak da zorluklar barınmaktadır. Piyanonun içinde algılayıcı yerleştirmek ve kablolama yapmak için alan çok kısıtlıdır. Bu yüzden, yapılan çalışmaların bazıları, veri toplama, algılayıcı yerleşimi ve kablolama için alan açmak adına, komşu tuşlar sökülmek üzere, tek tuş ile yapılır. Bunun sonucu olarak, deney içeriğinde, bir eser, pasaj veya egzersiz çalımı gerçekleşemez, tek tuş ile basış denemeleri yapılır. Piyanodan değil de, piyanistten veri toplayan hareket yakalama (MoCap), elektromiyografi, elektroensefalografi vb. sistemlerde de piyanistin bedenine yerleştirilen eklentilerin, piyano çalım deneyimini etkileme ihtimali vardır. Her ne kadar, bu tip olumsuzluklardan bahsedilebilse de, kantitatif çalışmalar piyano eğitimine büyük fayda sağlama potansiyeline sahiptir. Bu tez kapsamında geliştirilen teknoloji de tüm bu olumsuzlukların üstesinden gelebilecek şekilde tasarlanmıştır.

Newton'un etki-tepki prensibine göre, piyanistin, piyano çalarken parmak ucunda hissettiği her şey piyano tuşu tarafına da aynı şekilde yansır. Piyanistler, bu hislerini, kelimelere dökmekte zorlansalar da piyano tuşları, yansıyan bu hisleri, uygun algılayıcılar vasıtasıyla verilere dönüştürebilirler. Piyano tuşlarına uygulanan kuvvetlerin incelenmesi, daha iyi piyano çalmak adına bir çok nesnel çıkarıma olanak tanıyacaktır.

Dijital piyanolar ve dijital piyanonun sessiz çalışma avantajlarını da barındırmak üzere algılayıcılı üretilmiş akustik piyanolar olsa da, bu piyanolardan edinilebilecek veriler, nota şiddetlerini, başlangıç ve bitiş anlarını içeren MIDI verileridir. Bu veriler sadece çıkacak sese dair değişkenler olup, tuşa basış sürecindeki kuvvetlere, hareketlere ve postürelere dair bilgi barındırmazlar. Bu tez kapsamında, piyano çalıma dair kantitatif verilere ulaşmak adına kuvvet algılayıcısına dönüştürülmüş bir piyano tuşu tasarlanmıştır. Piyano tuşunu, kuvvet algılayıcısına dönüştürmenin altında, uzama pulu (strain-gauge) adı verilen algılayıcıların, piyano tuşunun hesaplar sonucunda belirlenmiş noktalarına, belirlenmiş açılarla yapıştırılması yatar. Uzama pulları, yapıştırıldıkları yüzeydeki uzunluk (şekil) değişimleri sonucunda son derece hassas voltaj değişimleri yaratan devreler oluşturan algılayıcılardır.

Bu çalışmada, piyano tuşlarını kuvvet algılayıcısına dönüştürmek için üç ayrı tasarım denenmiştir. İlki, tuşun piyanist tarafından görünmeyen bir kısmından bir parça kesip oluşan boşluğun alt ve üst kısmına üzerinde uzama pulları olan birer alüminyum levha yerleştirilerek yapılmıştır. İkincisinde, özel olarak tasarlanan, uzama pulları barındıran alüminyum bir blok, yine tuştan alınan bir kesit yerine yerleştirilmiştir. Son olarak ise, ilk iki prototipteki sorunların üstesinden gelebilmek adına, daha sağlam olması ve oluşan şekil değişimlerini yerinde ölçebilmek için, uzama pulları doğrudan tuşun üzerinde farklı noktalara yapıştırılmıştır. Bu son prototipte, tuşa gereken esnekliği sağlayabilmek için, fazladan delikler açılmıştır. Bu müdahalelerin mevcut piyanoya zarar vermemesi için piyano tuşları ölçülmüş, tasarımları sanal ortamda hassaslaştırılmış ve bu ölçüler doğrultusunda yeni piyano tuşları imal edilmiştir. Her tuşta bulunan dört adet uzama puluna bağlanacak, tuşun hareketini en az etkileyecek kadar ince, esnek kablolar temin edilmiş ve uygulanmıştır. Uzama pulları, tuştaki şekil değiştirmeleri ölçerken, tuşun hareketini ölçmek için doğrusal potansiyometrik yer değiştirme algılayıcıları, özel olarak tasarlanan levhaya yerleştirilerek tuşlara bağlanmıştır.

Nihai prototip tuşlar ile yapılan testlerde elde edilen veriler dolayısı ile *staccato forte*, *legato forte* ve *legato piyano* tipi çalışlar ile, tuşun zamana bağlı yer değiştirme ve şekil değiştirme değerleri elde edilmiştir. *Staccato* çalımda kuvvetin daha kısa süre *legato* çalımda daha uzun süre tatbik edildiği gözlenmiştir. *Piyano* ile *forte* çalımlarda, tuşun yer değiştirme-zaman eğrisindeki eğim farkı gözlemlenebilmiştir. *Piyano* çalımlarda tuşun temas edilen ucunda şekil değiştirmelerin (strain) daha az olduğu görülmüştür. Farklı tekniklerle çalınan bir trillden (iki yanaşık notanın hızlı değişimleriyle elde edilen müzikal süsleme) elde edilen verilerle, tekniğin değişiminin kaydedilen verilere ve grafiklere yansıdığı gözlemlenmiştir. Tuşa basıldığında tuşta ve mekanizmada oluşan geçici dinamik zorlanmalar ve mekanizmanın işleyişinin farklı aşamalarına dair bulgular grafiklerde tespit edilebilmiştir.

Bugün teknolojik imkanlar yardımı ile virtüöz piyanistlerin becerileri, kantitatif yöntemlerle incelenebilir ve bu incelemeler ışığında ortaya çıkan bulgular, piyano eğitimine daha önce hiç olmadığı kadar güvenilir önermeler sağlayabilirler. Piyano bilimi diye de adlandırılabilecek bu kantitatif yaklaşımların bazı kısıtları ve geleneksel öğreti içinde yer bulmalarına dair dirençler mevcut olsa da bugünün teknolojisinin yardımıyla geliştirilecek bir piyano eğitim sistemi ile piyanistlerin eğitimi çok daha verimli hale gelebilir. Bu tez kapsamında meydana getirilen bu sistem, yan yana tuşlara uygulanabilmiş, piyaniste görsel veya dokunsal olarak sıradan bir piyano tecrübesinden farklı bir deneyim sunmamayı başarmış, hassas ve güvenilir veri üretebilmiştir. Patent başvurusu yapılmış bu yeni önerilen sistem ve yöntem, piyano virtüözitesinin açıklanmasında önemli bir rol oynamaya adaydır.

# 1. INTRODUCTION

Piano with its historical context and technology is an exclusive machine that humankind created. It maintained an efficient point for the flourishing of famous pianists who are maybe the first pop stars of history. That era was the 19$^{th}$ century which is known as the rise of individualism and the grand piano was the ultimate device to express the inner self and also the physical capacities of the individual human with its vast frequency spectrum, extremely dynamic range, incomparable polyphonic opportunities and amorphous and also elegant surrealistic shape. Having such properties, the piano has been had maybe the most well-instituted education from these days on but on the other hand, incorporation of scientific approach in piano education did not proceed as it is expected.

Otto Ortmann (1925) gives scientific explanations based on objective experiments for playing the piano, investigating kinematics of piano keys and the touch types. Various scholars have continued trying to explain how to play the piano better. Unfortunately, this attitude could not find its place in the piano world and the dominance of non-quantitative tradition survives even nowadays. Mimaki (2010) says that most pianists are not familiar with the physiology of piano technique, lack the ability to diagnose technical problems with the piano and make adjustments to their technique, do not have the vocabulary to communicate their needs. Mimaki adds that pianists mostly do not listen to the sound that the piano is producing and rely more on touch than sound which is another example of lack of awareness during piano playing. According to Parncutt (2007), student pianists have a shortage of information on piano playing. They don’t know how the human body and the piano works, how the timbre changes in a particular piano, the noises of piano and the voicing of polyphony so the pianists may be called to be intuitive rather logical. Seymour Bernstein, in his interview with Ben Laude, told that even if their teachers had given them some instruction, they (all pianists) had to figure it out ourselves. He meant that learning how to use the body in piano playing, even in the best schools, is a virtue for the student to acquire herself/himself (Tonebase Piano, 2020).

It is said that a contrasting situation of musical performance relative to sports is the lack of scientific studies, which limits musicians accomplish emotional and virtuosic performance without developing injuries. The definition of Scientific Method in Merriam-Webster Dictionary (2021) emphasizes the collection of data through observation and experiment, the formulation and testing of hypotheses.

However, mostly, the knowledge on how to play the piano is not based on tested hypotheses. If sports science could become highly functional today, there should be a systematic, quantitative and cumulative knowledge for piano playing also.

### 1.1 The Need for Better Recordings, Better Performances, Better Training

In order to compare today's performances with the past, one may refer to today's hi-fi recordings, early recordings, the scores, letters of composers and their pupils', etc. The music scores handwritten by composers and iteratively published by companies gives hints on performances of the pieces in those days. Early recordings had been made under certain circumstances and they have to be evaluated under consideration of these constraints but still, they are the most precious information that links the performance tradition before the recording age to today. And today, although the highest resolution and the bitrate that can be considered as high fidelity to the real is obtainable easily, facilities served by technology made one think twice whether it is a close representation of the real or a utopic hyper-real. A recent case of such a concern can be given as Joyce Hatto, who was once thought of greatest pianist of the 20$^{th}$ century, turned to be the greatest music fraud ever (Finell, 2008). Opportunities served by new technology made her husband be able to manipulate other pianists' recordings and label them as "by Hatto". Interestingly, there are dedicated listeners who still prefer these interpretations to their originals.  Not only Joyce Hatto, but also almost all classical music recording industry uses overdub facilities of digital audio workstations (DAW). Recording by section to section, iteratively then choosing the best ones and glueing them together became a standard procedure. These raise the questions such as if a piece can not be played from beginning to the end as they wanted, why it's hard to play as intended, what the desired image of music (the ideology) is.

The debate over whether technology affects the ideology or vice versa has not ended yet. In the approach of the author, the ideology is the music, particularly, the way of playing the piano. Thus, the piano as a machine is the chosen technology parameter which is constantly evolving since Bartolomeo Christofori (1655-1731) pioneered the musical instrument called pianoforte, which has an action that enables playing different dynamics within a single keyboard, for the first time. Turning back to the debate on technology versus ideology, so piano action design versus interpretations of music, it is hard to define which one influences the other more but the change in both of them is obvious through history.

The piano mechanism, the technology, has transformed over the years, mostly towards the louder. As the outcome, the piano, which can sound louder, had to exhibit some sacrifices. So, the modern piano has some disadvantages to playing baroque, classical and even romantic piano repertoire over the pianos used during the creation times of that literature. The ideology pianists seek after today is maybe the traditional virtuosic playing which is more difficult to achieve with modern piano. On the other hand, there still exist super virtuosos today performing astonishingly.

Since the era of pre-recorded music, the population of the world highly increased, piano music became more global and achievable by various social classes, so the number of piano players increased but the proportion of players who can achieve the traditional playing regarding tempi, dynamics and sonority decreased. It is said that even music schools do not consider the tempo markings by Chopin in his etudes compulsory to achieve. However, although they consist of a small ratio of all, there still exist players who can do it regardless of their age. Twelve years old George Li could play Chopin Op.10 No.2 with 152 beats per minute (BPM) despite the disadvantage of his small hands and weak muscles if compared with an adult (George Li – Pianist, 2008). It is even higher than Chopin’s original tempo identification on the score which is 144 BPM. It is easy to find other extraordinary performances like this. The main question is how this less amount of pianists can still reach that ability to express that ideology although the change in piano technology made fewer amounts of people achieve it.

Vladimir Horowitz carried his own piano which has hammers replaced with lighter ones. The explanation of this:

Horowitz required precisely 44 grams of key resistance, but full-size hammers were too heavy for an action of this gram-weight; the average Steinway is weighted to approximately 50-55 grams. The result is an extremely fast action that is difficult for most pianists to control at first because they are accustomed to other pianos that have greater resistance to the fingers. (Hughes 1996, as cited by Mimaki, 2010,p.35)

Glenn Gould made his technician adjust the aftertouch of his piano extremely close to strings. This resulted in frequent wearing out in mechanism but he could accept this challenge (Mimaki, 2010). Joseph Hoffmann, the first perfect virtuoso pianist and Daniel Barenboim are known to employ a piano with narrower keys due to their small hand size (Keyboard Size, n.d). Moreover, pianos are still changing. Thus, the technical playing of past pianists cannot be referenced directly. One should consider the changes in hammer size so the touch weight, string thickness, key depth, and various related parameters. It can be said that earlier pianos were easier to play; but still, people needed to search for helpful devices that claim to be useful for employing a better technique. Virgil Practice Clavier (Figure 1.1), from the 19th century, was sounding only a click sound but the resistance of the keys could be adjusted up to enormous degrees (Virgil Practice Clavier, n.d.).


**Figure 1.1 :** Virgil practice clavier.

Logier's Chiroplast, Herz's Dactilion, Martin's Chirogymnast, Retif's Ochydactyl are devices invented in order to assist in gaining flexibility and true hand posture for piano playing in a shorter time than practising along (Predota, 2018a, 2018b;Fitch, 2013). Today, a machine named Presto Fortissimo gives extra power to touch strike so pianists can achieve more virtuosity with the help of it (Faulhaber, n.d.). As a result, although famous pianists have great ability to play the instrument, they searched for more ways to gain more dexterity. Researchers interested in making a scientific investigation on piano technique should approach the famous pianists and old pianos regarding (i.e. without neglecting) these aspects.

In fact, all the piano playing methods carry the students up to a certain level but the mystery is how top virtuosos like Arcadi Volodos, Yuja Wang, Lang Lang, Marc Andre Hamelin, Martha Argerich, Daniil Trifonov are able to play at their respective levels of virtuosity. They perform the same pieces as all other pianists in the world do, but they can do it what is so-called better. They are the most famous pianists and the most distinctive feature of them is their high level of technique and the wide range of possibilities they can exhibit to interpret the pieces coming from their technique level. Building a new piano education system upon data gathered from skilful pianists by quantitative methods that can be called piano science has a huge potential for more effective piano education.

### 1.2 Piano Technique and Education

The phenomenon called the technique of the pianist is the combination of various forces, postures and movements. These postures and movements should become habits or second nature to work efficiently. If one needs to gain a new skill, so a new habit, these new postures or movements should be repeated (i.e. practised) by the trainee for months to make them work like a "habit" (second nature). There comes the core dilemma of piano technique: If something cannot be played as aimed, are the forces, postures or movements wrong or have they not been practised (i.e. repeated) enough? This ambiguity is the main reason for the loss of time (ineffective utilization of training duration) during piano education. The solution to this problem is to quantitatively detect the right forces, movements and postures (i.e. skills) from pianists who can play as aimed.

As it has been illustrated in Figure 1.2, different posture-movement combinations may yield to same force profiles on keys. Also, different force profiles can yield almost the same acoustic output from the piano (i.e. sound).

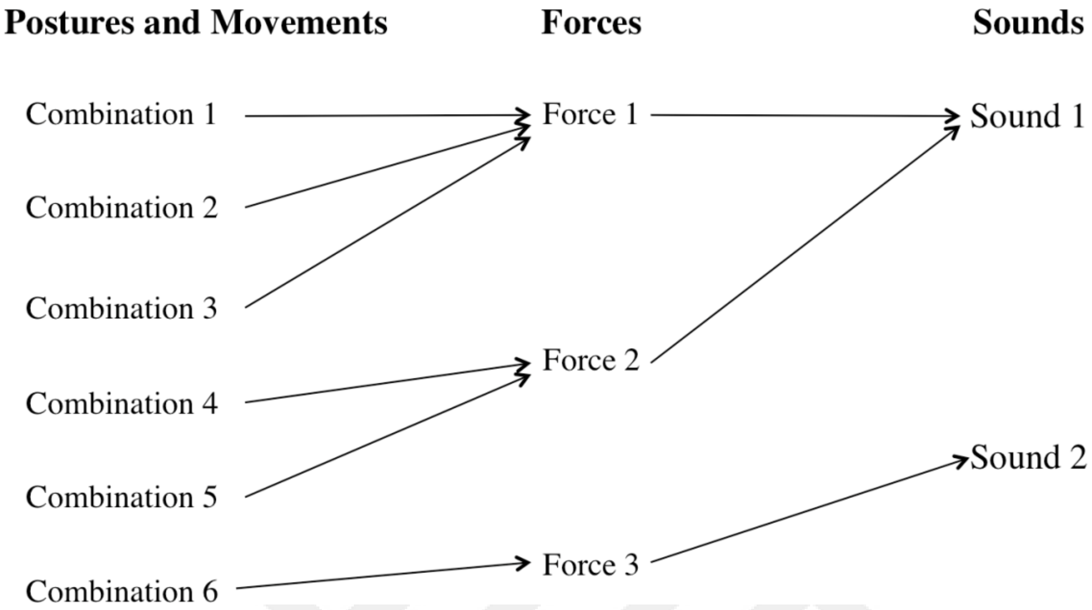


**Figure 1.2 :** Posture-movement combinations, forces, sounds.

Although different posture, movement, force combinations may result in the same sound in a slow tempo, such postures, movements and forces do not guarantee to yield the same acoustic performance at faster tempi. So in order to quantify the technique of the pianist, measuring the force and displacement profiles on the keys is beneficial. However, solely the human hand has 23 degrees of freedom (DOF) itself (Tits et al., 2015). Having said that, another reality is that different concertist pianists have different physiologies and use their bodies differently, but all are successful artists. So, it may not be said that there is only one right way to play the piano but multiple ways; and thus, multiple wrong ways. Under such circumstances, there are a lot of different arguments on how to play the piano by piano educators.

# 2. REVIEW OF LITERATURE

## 2.1 History of Piano Pedagogy

The piano was invented by Bartolomeo Cristofori in 1709, but it took time for the piano to be accepted. It is said that Johann Sebastian Bach tried a piano produced by Silbermann and disapproved of it due to its heavy keys and weak treble. Although there were works previously published with the phrase 'for harpsichord or piano', the first work composed directly for piano was Muzio Clementi's Op.2 Piano Sonata, published in 1773. Meanwhile, by Wolfgang Amadeus Mozart, Clementi is told to be the most important pianist after himself (Gerig, 2007).

Claims about how better piano players achieve this have continued to be made since the end of the 18th century but no agreement has been reached on this issue. According to Bermann, the frequently used French, German, Russian Piano School terms cannot be safely separated in terms of piano playing techniques, as they are heavily influenced by each other (Berman, 2000).

According to Hosaka (2009), some pedagogues focus on finger strength, some on arm weight, and some on a more intellectual approach. It is very difficult to put into words the kinesthetic feeling experienced by the piano player also it is easily misunderstood. Thus, finger strength exercises can cause tension, fatigue and injuries, while forearm rotation and arm weight techniques can cause flabby fingers. However, each approach will provide varying degrees of benefits in different situations.

When the finger technique school is mentioned, names such as Jean Francois Couperin (1668-1733), Philippe Rameau (1683-1764), Muzio Clementi (1752-1832), Johann Baptist Cramer (1771-1858), Johann Nepomuk Hummel (1778-1837), Carl Czerny (1791-1857), Charles Louis Hanon (1819-1900) come to mind. The finger technique school can be said to be the result of the transfer of the harpsichord technique to the piano. Although the two instruments differ in timbre and mechanical function, they have similar-looking keyboards. Accordingly, only the fingers should be active, while the rest of the body, especially the arms, should remain passive. The elbows are fixed so that they touch the body. Practising is generally done by raising the fingers as high as possible and pressing the key vigorously. Repetition of the same passage, if necessary, excessively, until you can play it properly, is the basic attitude of this teaching. The belief that it is necessary to spend hours at the piano every day is a proposition firmly accepted by the finger technique school. Carl Czerny, who wrote over 1000 studies and had students such as Franz Liszt (1811-1886), Adolph Kullak (1823-1862) and Theodor Leschetizky (1830-1915), among the names mentioned above, is a member of the finger technique school. He is also considered to be one of the first pedagogues to give relative freedom to the wrists and arms. Although different approaches flourished in relation to changes in piano mechanics and musical aesthetics over time, rules that came out of finger technique school continue to survive. Just as Heinrich Erlich based finger technique in his relatively late 1879 work ¨How to Practice Piano¨, in 1893, Hugo Riemann recommended Rameau's ¨Pieces De Clavecin Avec Une Methode Pour La Mecanique Des Doigts¨ which is solely finger technique, to piano teachers (Kochevitsky, 1967). Publications by Lebert-Stark which are outcomes of finger technique school were highly influential in the second half of the 19$^{th}$ century.

Joseph Pischna (1826-1896) and Aloys Schmitt (1788-1866) also published plenty of finger isolation exercises. Theodor Wiehmayer (1870-1947) argued that the problem with finger exercises is that they work all fingers equally, instead, this type of exercise should be done mostly for the fourth and fifth fingers. According to Kochevitsky (1967), Alfred Cortot (1877-1962) also repeated Hummel's hundred years old approach in his work called ¨Rational Principles of Pianoforte Technique¨, although he added some freedom to the wrists. So it can be said that, although other approaches have dominated from time to time, each approach on how to play the piano better has continued to be applied with other approaches.

In this period, besides exercises and studies aimed at structuring the fingers, mechanical tools was also used. In Figure 2.1, the Chiroplast, patented by Johann Bernhard Logier in 1814, was a tool that required the fingers to press the keys without using the force of the arm, by holding the wrist from above and below (Sakai 2002, as cited by Hosaka 2009). Later, in 1830, Friedrich Wilhelm Kalkbrenner introduced the Hand Guide, which was easier to use without the upper support of the Chiroplast and again prevented the use of arm weight.

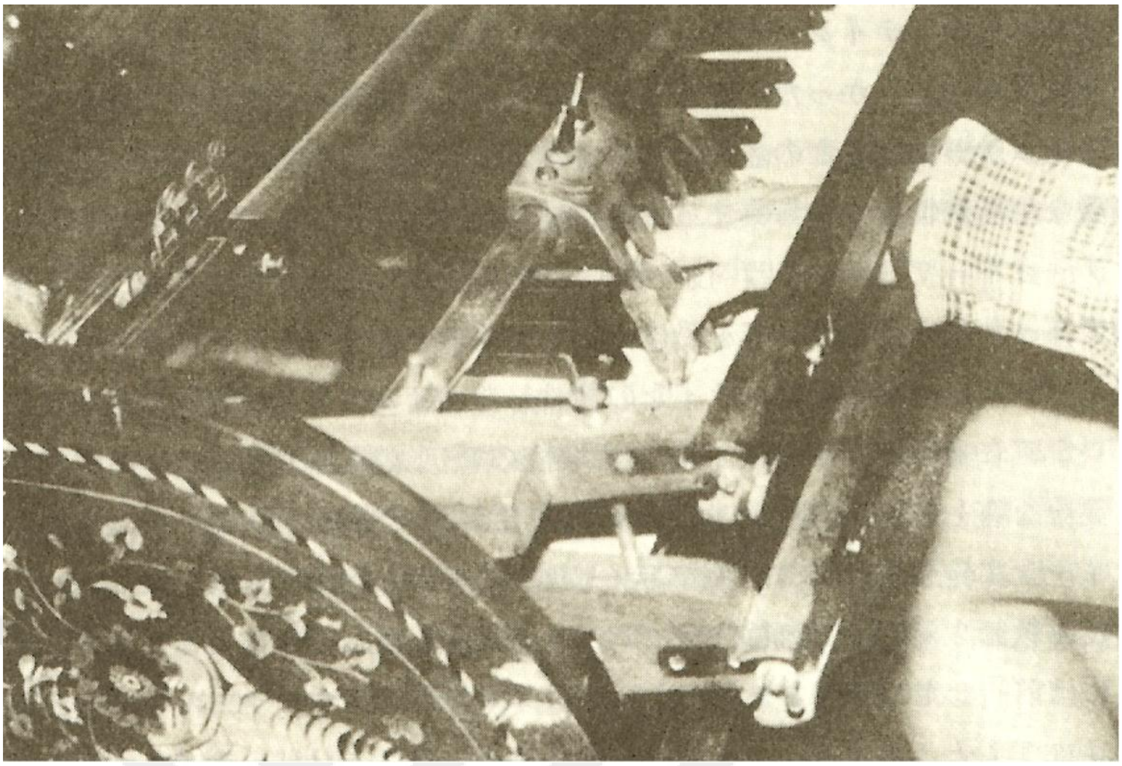

**Figure 2.1 :** Chiroplast.

The Dactilion shown in Figure 2.2, invented by Heinrich Herz, was an auxiliary device consisting of springs attached to worn rings to strengthen the fingers (Classicfm, 2017).

**Figure 2.2 :** The Dactilion.

As shown in Figure 2.3 the Ochydactyl, is a device for strectching the fingers (Classicfm, 2017). It is invented by Georges Rétif in 1922, promised to increase pianists, violinists, and cellists' finger agility, flexibility, strength, and independence, with seven minutes of use corresponding to an hour of typical finger practice. Four fingers would be inserted into the adjustable, rubber-padded clamps, with the musician's wrist resting on the seat. The musician would use his other hand to crank gears in either way, moving his fingers up and down. The passion for equalizing the fingers lead to the execution of a surgical operation that cuts the tendons between the 4th and 5th fingers was discussed in musical and medical publications in the 1880s. The claim that it would facilitate progress in the piano was not accepted in Europe, but it was applied in America, resulting in negative results (Kochevitsky, 1967).

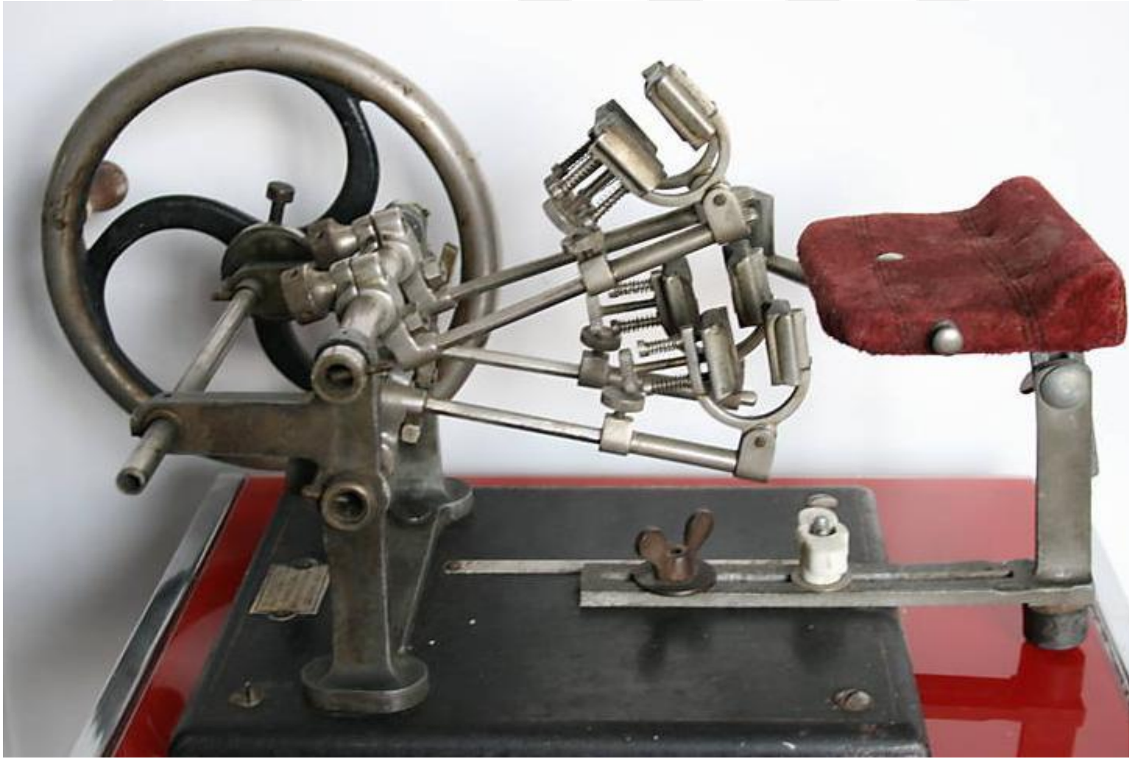

**Figure 2.3 :** Ochydactyl.

If one reason behind this great effort to strengthen, accelerate, stretch and equalize the fingers is the switch from harpsichord to the piano which has heavier keys (or feels heavy because it is not as bright as the harpsichord), another reason is the evolution of the piano itself. The constant increase in the key resistance and string tension prevented the development of many pianists who surrendered to the strict rules of the finger technique school, and pedagogues headed towards to find other solutions. Also, a new approach in musical aesthetics (Romanticism) is certainly another reason for the need for innovation in technique. Chopin, Kalkbenner, Thalberg, Anton Rubinstein underlined the necessity of listening to good singers in order to play the piano better.

Although Robert Schumann's teacher and Clara Schumann's father, Friedrick Wieck, focused on finger technique using Chiroplast in his early years, is known that later abandoned this attitude. Robert Schumann argued that technical studies shouldn't be the focus of practice. He claimed that the more important thing is to listen to oneself and to perceive the structure of the music. Although Frederic Chopin was not very interested in piano pedagogy, he accepted the inequalities of the fingers and positioned the hand accordingly. In addition, he says that the elbows should be opened as the hands are opened. Although he says that the hand should not be turned during the thumb pass-overs, in many other situations he defends the flexibility of the wrist. Franz Liszt published finger technique studies in his early years. Then, he said that in his later years, the finger should work with the participation with the whole arm and all priority should be given to the tone, not to the technique. Although Theodor Lechetizky is from the finger technique school, he especially drew attention to the activity of the wrist. He is against mechanical work, he puts the mind in the foreground. In fact, he stood in the middle of the old school and the new school, maybe that's why the most talented students lined up to study with him in those days.

Beyond these mild deviations, Adolf Bernhard Marx (1795-1866), Adolph Kullak (1823-1862) and William Mason (1829-1908) were among the first teachers to talk about the insufficiency of finger technique (MacRitchie, 2015). This new approach is named as anatomical-physiological school by the pianist, musicologist Grigori Kogan (1901-1979) (as cited by Kochevitsky, 1967). But the pioneer of the anatomical-physiological school was Ludwig Deppe (1828-1890). Ludwig Deppe opposed the high finger exercises and drew attention to the importance of using the weight of the arm instead of trying to strengthen the hand and finger muscles which are structurally weak. Deppe incorporated the concept of free fall into his piano technique. Instead of using a hovering quiet hand/arm, which is a pre-acceptance by the finger technique, the relaxation (heavy or loose arm) approach is emphasized. He suggested the rotation of the forearms, swinging upper arms, circular movements and extended elbows. By opening elbows, the hands are inclined to the thumb so each finger can touch the keys perpendicularly. For this reason, it can be said that Deppe is the beginning of the arm weight school.

Leaving aside the limitations of finger technique, biomechanics became a highly significant research area. An absolute, ideal piano technique that fits everyone was tried to be found. Rudolf Maria Breithaupt (1873-1945) and Tobias Matthay (1858-1945) followed the path opened by Deppe in this direction. Matthay revealed that there are 42 types of keypress and said that one should think of the key as the continuation of the finger. The terms weight playing, relaxation, loose and heavy arm became widely used. The obligation of working for several hours every day is rejected. All technical problems can be overcome if the working principles of the muscles are solved. So an approach that tries to explain the positions and functions of the muscles has been developed.

However, this understanding had some problems. Their drawings and explanations on anatomy were not acceptable by the medical community (Kochevitsky, 1967). In addition, Deppe's definition of freefall was later updated by students as controlled freefall. Breithaupt had to update his book "The Natural Piano Technique" four times, while Matthay had to publish a second book explaining his first book. In fact, a student of Matthay found it necessary to publish a separate publication named ¨What Matthay Meant¨. According to MacRitchie (2015), many of the suggested training methods are mostly based on the personal experiences of the authors. These kinesthetic experiences are very difficult to express and the possibility of misunderstanding is very high (Hosaka, 2009). While Kochevitsky (1967) severely criticizes all these approaches, he attributes the fact that many great pianists were able to grow up in these periods, due to the fact that real talents sometimes have the ability to find the right path, even if it is the opposite of what they were taught. Kochevitsky adds that the spread of this approach lies behind the claim that it is possible to play effortlessly which is against the no pain no gain approach of the previous school (Kochevitsky, 1967).

Despite the scepticism for the objectivity of the anatomical-physiological school, Marie Jaell (1846-1925), Oscar Raif (1847-1899) and Otto Ortmann (1889-1979) have done considerable objective experiments on piano playing. By sticking special cards on the key surfaces, Jaell tried to make assumptions about the touch and timbre relationship based on the changes in the fingerprints on the cards after certain exercises were accomplished by subjects (Weinstein-Reiman, 2020). Oscar Raif, by comparing the finger tap repetition rates of pianists and non-pianists, stated that finger exercises do not accelerate the fingers (Raif, n.d. as cited by Kotchevitsky, 1967). According to him, there is no difference in the finger stroke repetition rate of a small child and someone who has studied the piano for years. What limits this speed is our auditory perception, and this is a maximum of 12 repetitions per second. Whereas, for example, Sviatoslav Richter was able to play Chopin's op.10 no.4 etude with a tempo that equals to 14.4 keystrokes per second (Sturrock, 1999). However considering that the lower limit of perceiving a repetitive pulse as a sound is 20 pulses per second, it can be accepted that he did not make such a far claim. He asserts that what underlies good playing is not the speed of the finger, but the coordination between the fingers to play the keys that need to be pressed one after the other. Ortmann (1925), on the other hand, examined the body within the framework of mechanical laws. He treats the pianistic limbs as the third type of levers (like tweezers). According to him, a muscle works in cooperation with the opposing muscle and what lies behind good piano playing is not complete relaxation. When a muscle relaxes, its opposite contracts. He says that the muscles which move the joint contract in all directions in order to keep the joint stable. He suggested that the only parameter that the pianist can affect to control the key is the speed of pressing, apart from that, there are two types of keypress, pressed and struck. He supported all these claims with his experiments with measuring devices called dynamograph and ršntgenogram. In contrast, Yale University Head of Piano Department Boris Bermann (1948-) mentions six variables of keystroke in his book ¨Notes from Pianist's Bench¨. He named these as weight, mass, velocity, depth, finger posture, finger contact point but did not provide a measurement of these variables (Berman, 2000). Heinrich Neuhaus (1922-1964), who is also a very important figure from the 20$^{th}$ century, the teacher of legendary pianists such as Emil Gilels and Sviatoslav Richter, emphasized the importance of circular movements by expressing that the shortest distance between two points on the piano is not straight, but curved. Although he does not give much technical advice and he does not put forward an objective basis to support his pieces of advice in his book (Neuhaus, 1993).

Whether it is based on individual experience or supported by objective experiments, there have also been approaches that emphasize the mind, imagination and intellectuality against all these mechanical and analytical approaches. And these psychological approaches have been said more loudly over time. According to supporters of this school, knowing how the body works can not give ultimate control of it. It has been suggested that the passages that cannot be played as desired should be practised properly in the mind first, and then the correct movements can be applied spontaneously (Kochevitsky, 1967). The effect of neuromuscular differences on the piano playing is an important question. Although, Wagner (2012) said that there couldn’t be found significant muscular difference between pianists and not pianists , Leon (2017) claims the improved physical conditioning, which goes hand in hand with accurate neural representation of the precise mechanical necessities for the desired movement improve mental conception and listening. According to Kochevistky, the main apparatus to develop for piano playing is central nervous system. He adds that the basis of the talents of great pianists who studied old methods is that they can go beyond the strict limits imposed on them by their teachers due to their extremely vivid image (Kochevitsky, 1967). There are numerous identities and arguments within the neuro-psychological school of piano playing but these are out of the scope of this dissertation.

According to Swiss physician and philosopher Paracelsus (1493-1541), all things are poison, and nothing is without poison; the dosage alone makes it so a thing is not a poison (Grandjean, 2016). Analogous to this, each suggestion to piano playing has its benefits on the player but the distinction lies behind the amounts of these implementations in musical life.

## 2.2 Miscellaneous Approaches on Piano Playing

There are piano playing schools that are concentrating on injury-free piano life. Some of them, like Taubmann Technique, also claim that such a healthy technique is the way to virtuosity. The Taubmann Technique which is constituted by Dorothy Taubmann (1917-2013) has maybe the most documented material among all of them, where deep explanations of movements and their healthy ranges are well defined. It rejects finger individualization and strengthening exercises. Forearm rotation, in-and-out (inwards and backwards motion of the wrist), walking arm (abduction and adduction of the elbow and forearm) and shaping (circular movements of the wrist) are four fundamental movements. All the finger work, thumb pass overs, jumps etc. must be played using forearm rotation (Taubmann, 2005). Being totally against finger independence, the Taubmann Approach is an extreme example of the anatomic-physiological school.

Vincenzo Scaramuzza (1885-1968) was an Italian pianist and music teacher who moved to Argentina in 1907, began to teach at Santa Cecilia Academy of Music, in Buenos Aires and founded Scaramuzza Academy of Music in 1912. Argentina, besides not being located in the Old Continent, is a country where many legendary pianists of eurogenetic music were born in, such as Enrique Barenboim (father of Daniel Barenboim), Martha Argerich, Michèle Boegner, Bruno Leonardo Gelber, Carmen Piazzini, Daniel Levy, Mauricio Kagel, Fausto Zadra, Alberto Portugheis, Maria Cristina Filoso and Monica Stirpari among others. Also, Argentina's own music genre tango had great pianists too. Some of these are Arminda Canteros, Osvaldo Pugliese, Horacio Salgán, Atilio Stampone, Orlando Goñi and Sylvia Kersenbaum. All of these great names had a common instructor named Vincenzo Scaramuzza. The main area of concentration by Scaramuzza was on relaxation of pianistic tools and awareness of the body. Although his approach seems objective, most of the explanations refer to metaphors like resemble of tendons to elastic bands. According to Lian (2013) Scaramuzza put forward critical technical tips like the use of an active wrist, which can be traced in legendary octaves of Martha Argerich who claims that she did not need to study any etude, make any warm-up. Martha Argerich is one of the biggest virtuosos today and her manifest gives point to the relaxation attitude of her early teacher, Scaramuzza. Besides her visible active wrist, she seems to use flat fingers and high knuckles with metacarpal flexion of the fingers (Nanev, 2017). Scaramuzza's approach resembles mostly the anatomic-physiological school.

Resources from Japan on piano playing are mostly in Japanese, but one of the exceptions is the dissertation titled "Sumiko's Piano Method: A Modern Physiological Approach to Piano Technique in Historical Context" (Hosaka, 2009). According to Hosaka, finger independence, muscle strengthening and flexibility are must for Mikimoto's piano pedagogy. Mikimoto built up exercises with and without a piano in this respect but also measured the application of exercises with a metronome and also weights. She also created a little wooden tool called fingerboard in order to help pianists develop small finger movement while playing *pianissimo*. Mikimoto claims that inequality of fingers differs from person to person, thus offering exercises that focus on detecting and working more on weaker fingers. Mikimoto's approach is close to the finger technique school.

Today there are numerous virtuosos pianist stars from China, some of whom are Lang Lang, Yuja Wang, Yundi Lee. According to Xu (2018), the finger strengthening exercises and utilizing the high finger technique is the main work out. According to healthy playing oriented medical perspective writers on piano playing, high finger technique has a comparatively high potential of injury due to frequent inflammation in and between extensor tendons lies in the forearm (Taubman and Golandsky, 2005). However, it is a common practice of piano education in China where these piano stars with incredible technique are coming from. On the other hand the –although Bermann does not accept national piano schools- Russian piano School, which is an extension of German Piano School by using arm weight dominantly according to Lourenço & Lourenço (2010) is seen to have an impact on Chinese Piano Pedagogy too according to Sun (2018). So Chinese Piano School mostly built on the finger technique which is an adaptation of early piano/harpsichord technique by using solely finger power but giving them more potential energy with lifting as much as possible remained the dominant attitude on piano playing.

Besides the established piano doctrines, one may also consider the discourses of living pianists on piano technique. In his own YouTube channel, Turkish pianist Emre Şen, analyzes piano pieces written by famous composers. In the third episode of this series, talking about J.S.Bach, he claims that analytical thinking on how to press the key is nonsense; instead, one should feel the colour of the note intended then the body will react according to this colour and states that the appropriate sound will be accomplished then (Şen, 2019). Zlata Chochieva, in a published video of the International Miami Piano Festival, shares her own observations on Chopin Etudes while performing them. In this video, she constantly expresses her search for the right timbre, claiming that all the technical problems will vanish with the right timbre, naturally. After a while, questions arise from the audience on how to practice and how to achieve such technical ability, but she insists on the right timbre and colour and the disappearance of the technical difficulties afterwards (Chochieva, 2016). All of these explanations are compatible with the neuro-psychological school.

According to Hmelnitsky and Nettheim (1987), most of the movements of fingers originated from the muscles lay in the forearm but also there are muscles called interossei and lumbricalis in the hand. Especially *piano*[1], *pianissimo* and *legato* playing needs well control of these tiny muscles. These exercises are the first step to use these muscles because they are not so powerful and the resistance of piano keys make the uneducated pianist use powerful forearm muscles in order to overcome that resistance. Instead, one should learn to use hand muscles and strengthen them to broaden one's palette of technical skills to be able to perform for the sake of one's own interpretation of particular music. These exercises are explained in a more anatomic-physiological school manner but the operation is similar to the finger technique school.

Beyond these, there are still countless explanations/methodologies for "better" piano playing. Without quantitative methods, it is impossible to reach an agreement on the efficiency of piano techniques. A sensor-based quantitative approach can measure the straining on the keys and detect whether the finger is pulled or pushed while playing. Also, sections like octaves and parallel chords or intervals can be played by both wrist and elbow etc. If the wrist is more active, again, there will be a possible change in frictional behaviour between fingertips and the keys due to variations in relative motion. Such differences change the straining patterns of the key itself which is measurable up to an extent with specially instrumented piano keys. A sensor installed piano keyboard can measure technical differences while using each finger and can detect weak fingers in certain positions and can be used as a strengthening tool for equalizing the response of fingers as much as possible. Sensors can detect the forces applied on piano keys while using different techniques which enables a quantification method that can be proven to be trustful to compare different approaches to play the same piece or passage. Measurements on playing through piano keys make it possible to find out weak notes during performances and these identified areas can help pianists to observe their hands fingers and see if there is a dependence or joint issue. However, on the other hand, the limit of detections that a

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[1] The word ¨piano¨ has to be used meaning both the musical instrument and the soft playing. In order to overcome this ambiguity, musical terms indicating loudness is written in italics.

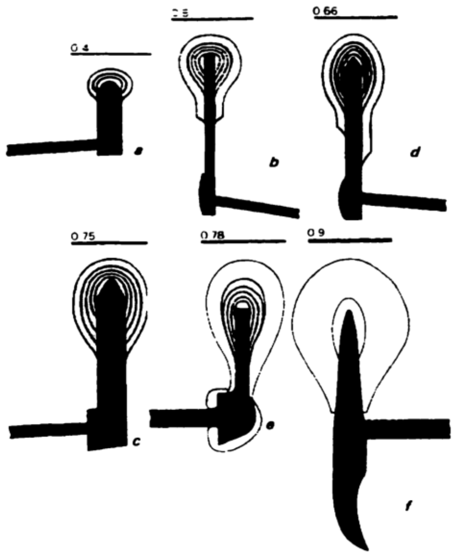
sensor installed piano can achieve is still unclear. Although elbows seem like distant parts of the body from the fingertip, still, their position may reflect on the direction of the forces applied through the fingertips. Despite all, instrumented piano keys have the potential to give quantitative and objective data to demonstrate the importance of elbow positioning while playing. With a sensor installed piano, experiments designed to capture not only exercises or simply key pressings but actual performances can shed light on differences or amount of variety of touch between virtuosos and ordinary pianists. Unfortunately, although the world getting dependent on data every day more and more, this approach couldn't find its function in piano education as much as needed.

### 2.3 Reasons of Uncertainty on Piano Technique

There exists quantitative research working on how to play the piano in a way with a more scientific basis but their approach have not yet been accepted by the majority of piano educator's world. This situation has a number of possible reasons. Under the stress of a highly competitive career, specialization in one direction became dominant and most classical pianists give up skills like composing, improvising, tuning, etc… They intrinsically employ the manifest of one shouldn't know how the car works in order to drive a car well enough (though it is not always the case). They are mostly closed to following the new findings in technology and the pedagogy in their field which makes it harder for them to collaborate with scientists conducting quantitative research in piano technique and piano pedagogy. Piano education is still a tradition that mostly begins in childhood. The vast majority of pianists are the ones that learned to play the piano at an early age through mimicking their tutors. Most of them are far from knowing the analytical basis of how they could learn/improve their playing skills. As a consequence, most of the pianists cannot explain how they have accomplished their way of playing. So their students can not obtain the desired knowledge of skills. Parncutt (2007) says that most of the teachers find the amount of provided education and amount of flourishing pianists adequate and rejects any methodical change all over. One reason for this may be performance teachers' feelings of disempowerment by their lack of familiarity with the content of the scientific findings. According to Parncutt (2007), performance teachers have a tendency to refuse an analytical approach for the sake of being an artist. However, Parncutt grants them rights because the necessity of performing well is being non-analytical somehow. Anyway, he adds that the analytical approach is still crucial for solving technical problems during preparing for the stage. Besides these, keeping important knowledge as a secret is a known attitude in music tradition. For example, iconic violin virtuoso Paganini has said to be never played in rehearsals as he plays on concerts due to the possibility of someone figuring out his tricks. Competition is merciless in music all over history.

Whether a pianist is a pedagogue or not it is hard for one to put in words how to play the piano in a certain way. Language is far from being absolutely effective to explain one's outer and inner world. This fact is valid for piano playing also. The words like tension, relaxation, tightness, etc… are used in different meanings in different resources on piano pedagogy (Wheatley-Brown, 2011). Also, ¨press to the bottom ¨ and *legato* are two main directions in piano playing but they couldn't have been described well enough yet. Idil Biret says that after she began to work with Nadia Boulanger, she learned the secret of piano playing which is *legato* playing (Xardel, 2006). In fact, *legato* is not thought to have a secret but a basic technic in piano playing that students accomplish in their first year of piano practice. Also, the ¨press to the bottom¨ direction is used to be said by Sen (1999) strictly but in the touch categorizations of Mimaki (2010) two of the four types of touch don't allow the key to touch the keybed.

The machine called piano evolved in time but piano education couldn't grow cumulatively on previous declarations on piano technique whether they are objective or not. The suggestions like finger technique and arm weight technique are not sufficient for today. As seen in Figure 2.4, the change in the piano is roughly towards louder and heavier in action (Ching-Yu Ho, 2000). The hammer sizes and the string thicknesses are increased over time. The strings are thickened twice from the end of the 18$^{th}$ century to the 1970's. Although there are no values of hammer weights, inflation in size can be observed easily.



a. South German (Heilman), c. 1785
b. English (Broadwood), c. 1806
c. Viennese (Graf), 1826
d. English (Broadwood), c. 1823
e. French (Erard), c. 1825
f. American (Steinway), c. 1970

**Figure 2.4 :** Change of hammer size and string thickness over time.

In Figure 2.5, touchweight for minimum sound (dampers on) comparisons between pre-1790 and 20$^{th}$ century pianos can be seen (Mobbs, 2001). According to Mobbs, touchweight of the middle C changed enormously in 200 years.

*Pre–1790 Pianos*

**'German/Viennese'**

| ref | | date | gm FF | gm $c^1$ | gm $f^3$ |
|---|---|---|---|---|---|
| 21 | Heilmann | 1775*c* | 39 | 32 | 25 |
| 49 | Stein | 1780*c* | 32 | 28 | 18 |
| MFA | Stein | 1783 | 40 | *30 | 23 |
| 66 | Stein | 1788*c* | 46 | 32 | 25 |
| 56 | Stein | 1788 | 36 | 30 | 25 |
| 15 | C&G 'Stein' | 1784 | 39 | 32 | 25 |
| | Mean | | 39 | 31 | 24 |

* extrapolated from value of 27gm for $c^2$ (*see* Koster[5])

**'English'**

| | | | | | |
|---|---|---|---|---|---|
| 47 | Backers | 1772 | 39 | 32 | 30 |
| 19a | Broadwood | 1787 | 59 | 43 | 41 |

**'Anglo/German'**

| | | | | | |
|---|---|---|---|---|---|
| 23 | C. Hancock | 1779 | 35 | 25 | 15 |

*Twentieth-century Pianos*

| | | | | | |
|---|---|---|---|---|---|
| 14 | Steinway | 1911 | 98 | 77 | 68 |
| 17 | Bösendorfer | 1931 | 89 | 82 | 68 |
| 16 | Steinway | 1951 | 103 | 80 | 78 |
| 18 | Estonia | 1980 | 128 | 110 | 103 |
| 19 | Steinway | 1982 | 101 | 83 | 77 |
| 6 | Steinway | 1983 | 101 | 89 | 83 |
| 5 | Steinway | 1983 | 95 | 80 | 77 |
| | Twentieth-century mean excepting no.18 | | 97.8 | 81.8 | 75.2 |
| | Mean of 1982/3 Steinways | | 99 | 84 | 79 |

**Figure 2.5 :** Change of touchweight over time.

In Figure 2.6, early and modern pianos are compared due to their keyboard geometry differences (Mobbs, 2001). The evolution of piano is not just towards the heavier but also the bigger. As shown in the figure, measurements of keydip, octave span, key length, black key width, black key distance give greater values as the date come closer to today.

| | *Pre–1790* 'German/Viennese' | | c.f. Table | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 7 | 8 | 9 | 9 | 10 | 11 | 11 | 11 | 11 |
| ref | | date | Key-dip mm | 8ve span cm | mean dist. betw. accs. top cm | mean dist. betw. accs. bott. cm | mean dist. acc. width top mm | acc. lngth top cm | acc. lngth bott. cm | lngth nat. cm | lngth key-head cm |
| 21 | Heilmann | 1775c | | 15.7 | 1.63 | 1.6 | 9 | 8 | 8 | 11.6 | 3.6 |
| 49 | Stein | 1780c | 7 | 15.93 | 1.65 | 1.45 | 9 | 8.65 | 8.85 | 12.6 | 3.75 |
| 36 | Stein | 1780c | | 15.7 | 1.71 | 1.56 | 9 | 9.05 | 9.2 | 12.75 | 3.55 |
| 70 | Anon | 1785c | 5 | 16.03 | 1.7 | 1.5 | 9.5 | 8.7 | 9.05 | 13 | 3.95 |
| 37 | Walter | 1785c | | 16 | 1.73 | 1.48 | 8.5 | 9.5 | 9.8 | 13.8 | 3.55 |
| 66 | Stein | 1788c | 6 | 15.8 | 1.6 | 1.4 | 9.5 | 9.1 | 9.25 | 12.9 | 3.65 |
| 56 | Stein | 1788 | 6 | 15.88 | 1.7 | 1.4 | 9 | 8.65 | 8.85 | 12.5 | 3.65 |
| | Pre-1790 mean | | 6 | 15.86 | 1.67 | 1.48 | 9.07 | 8.81 | 9 | 12.74 | 3.67 |
| 15 | C&G 'Stein' repro. | 1784 | 6.3 | 15.9 | 1.68 | 1.58 | 9 | 8.9 | 9.1 | 12.6 | 3.5 |
| | 'English' | | | | | | | | | | |
| 47 | Backers | 1772 | 7.5 | 16.22 | 1.63 | 1.53 | 9.75 | 8.1 | 8.4 | 13.05 | 3.95 |
| 19a | Broadwood | 1787 | 8.5 | 16.3 | 1.71 | 1.57 | 9.25 | 8.1 | 8.43 | 12.7 | 4.3 |
| | 'Anglo/German' | | | | | | | | | | |
| 23 | C. Hancock | 1779 | 6 | 16.57 | 1.68 | 1.4 | 10 | 8.1 | 8.4 | 12.7 | 4.3 |
| | *Twentieth Century* | | | | | | | | | | |
| 14 | Steinway | 1911 | 10.25 | 16.59 | 1.66 | 1.56 | 10 | 8.75 | 9.25 | 14.35 | 5.1 |
| 16 | Steinway | 1951 | 11 | 16.6 | 1.73 | 1.53 | 9 | 8.95 | 9.7 | 14.7 | 5 |
| 19 | Steinway | 1982 | 10.75 | 16.56 | 1.76 | 1.57 | 9.5 | 8.9 | 9.6 | 14.68 | 5.08 |
| 5 | Steinway | 1983 | 10.5 | 16.56 | 1.7 | 1.5 | 9 | 8.8 | 9.5 | 14.65 | 5.15 |
| | Twentieth-century mean | | 10.63 | 16.58 | 1.713 | 1.54 | 9.375 | 8.85 | 9.513 | 14.6 | 5.083 |

**Figure 2.6 :** Change of keyboard geometry over time.

Hammers, touchweight, aftertouch, key dip, key sizes, thickness of strings and resonance of piano have increased throughout history (Mimaki, 2010). Pianists who find a chance to play with a $19^{th}$ piano can play Chopin and Liszt Etudes far more easily than they can do on today’s pianos (Goettler, 2021; Samson, 2001 as cited by Salvosa, 2018). According to Berstein, the keys of Chopin's piano were so narrow that one octave was as narrow as the seventh of today's pianos. Therefore, playing the Op.10 No.1 etude was not as difficult as it is today (Tonebase Piano, 2020) .$18^{th}$

pianos are even easier to play. Nevertheless, they lack the sonority of the modern piano. Piano education would have been changed much more than it is than today. Quantitative research methods may close this gap with ease.

### 2.4 Previous Quantitative Works on Piano Playing

Today, data is more interpretable than ever before and having living super virtuosos despite over-loaded evolved modern piano makes scientific research extremely important to understand how the piano can be played more efficiently. Having the ability to reach the desired level of efficiency enables more varied interpretations of music. Scientific investigation of piano technique from the perspective of virtuosity has the potential of redefining or at least modifying the piano pedagogy. With the aid of this knowledge, pianists can achieve to perform the music desired by the composers and also by themselves. Such a tool offers the potential to build a new language for piano playing. In order to maintain the piano education standard close to the virtuosic piano playing, there is a need to reconstruct piano education based on new technological findings which have quantitative measures of feedback.

With the help of the developing engineering technology, measurement methods have become more diverse, more accurate and more affordable compared to even recent decades and these methods have been started to be applied for clarifying the piano playing techniques. While optical or magnetic motion capture systems can give data of changing positions of the player complex from a biomechanical point of view, electromyography (EMG) is a good source to draw a line for neuromuscular activity. Focus detecting binoculars, high definition slow-motion cameras, infrared-optic sensor tools of 3D kinematic motion and depth-sensing gesture tracking systems along with old reliable musical instrument digital interface (MIDI) data are among tools that can give us quantitative information on what is going on during piano playing.

Each type of measurement tool has its own advantages and disadvantages. But the motion capture systems are today's trend for academic research in this topic. Motion capture is a technique that has several transmitter/reflector units that have to be placed on moving parts of the body and one or more receiver(s) which can be cameras as well as magnetic capture systems. The receiver(s), after a pre-calibration, help to identify the position information of the transmitter units with respect to a fixed coordinate system and sends the transient motion bulk data to a computer where it can be further processed. One can utilize statistical methods like analysis of variance (ANOVA), draw graphics or even animation of that particular playing. The accuracy of motion capture systems is generally up to 0.1 millimetres spatial and 4-8 milliseconds temporal for mid-level systems. The optical motion capture has reflective or active markers as transmitters and a number of infrared cameras as the receiver while the magnetic motion capturing technology utilizes little metal pieces (spheres) and a metal detector type of receiver(s). The main advantage of magnetic type is the optical system's proneness to light interference and loss of vision. On the other hand, magnetic type can not measure in the presence of comparable metal objects in the control volume which has to be replaced by plastic or wooden materials. Also the markers are placed on the joints in optical system but magnetic one has advantage of placing markers on middle of the bones so they are more robust (Rahman, et al., 2011).

Various studies have utilized optical methods up to date for investigating piano techniques. In the experiment of Goebl and Palmer (2013), optical motion capture is used. Results show that to perform at fast tempi, finger movement efficiency is especially vital. To achieve the high levels of timing and force precision that is common among professional musicians who develop their piano technique through decades of practice, substantial movement control is necessary. In the work of Kelley et al. (2010), there are ten pianists and optic motion capture technology. Four of the two subjects are eliminated from analyses because of technical problems that occurred during tracking and collection of data. Results claim that despite findings do not differ considerably between the two groups, the standard deviations of the amplitude of joint motions of traditionally-trained individuals were higher than those of the ones trained according to Taubman principles, possibly indicating that the Taubman pupils' movements had lower amplitudes. According to Tits et al. (2015), the eigenvalues, which indicate the contribution of each eigenmovement (a well-defined and sequenced movement pattern that is independent of others) in the original (recorded from the pianist) movement, allowed pianists to be compared to one another. The outcomes of the study have revealed that highly skilled pianists used more eigenmovements, indicating higher hand motor control. Four pianists who are playing piano 15 ± 6 years participated in the experiment done with 12 motion capture cameras and 17 reflector points in each subject's hands.

Some research concentrate on torso movements during playing. That kind of observation does not need to be under millimetre accurate so more affordable solutions can be preferred. Hadjakos (2012) defines the advantage of using 3D depth sensing devices as piano pedagogy systems. They are effective in cost-sensitive less accuracy required scientific examination in musician medicine and performance research. But for high accuracy, depth-sensing fell behind the motion capture systems. Also, one depth-sensing device was found to be insufficient in order to evaluate torso movements of pianists during an experiment designed to expose efficiency of the device (Beacon, et al., 2017).

EMG can be used to measure muscle activity. There is a more accurate type of EMG that needs needle insertion but it is painful so there is an ethical consideration to limit the collection of this kind of EMG data. Comparing EMG data gathered by 15 college piano students and 15 non-musicians, it is found that during minimum muscle contractions, the pianists had a considerably greater firing rate, shorter duration, and amplitude of motor unit potentials than the non-musicians. When all the metrics were compared at different degrees of contraction, the pianists had a considerably greater firing rate only at 25% and 50% of voluntary muscle contraction, and a significantly larger amplitude at maximal contraction than the non-musicians. In pianists, the amplitude of maximal control contraction was higher than in controls (Lai, et al., 2008).

There are various works experimenting and investigating principles and measures of biomechanics applied in piano playing. Some of them put the fact that the variance of hand-spans is high among the great pianists. Legendary pianist Sviatoslav Richter could reach 12th intervals but Josef Hofmann could play utmost one octave. Lee (2010) reports that ¨pianist with a smaller hand and larger hand span had the pianistic advantage over a pianist with a large hand and smaller hand span¨. This work, thus, claims that the flexibility of the joints has the potential to be a leading biomechanical advantage. However, it is also found that hand span is a risk factor for piano-related injuries (Patterson et al., 2011). The experiments also show that left hand spans are wider than right hands. That is the evidence of adaptation of biomechanics. Besides adaptation, there are various differences pointed out between genders, an example of which is the greater amount of ranges of both active and passive movements in female pianists compared to those of male pianists. Also, the weights of hands are seen to be different in men and women but no common pattern in performance output could be demonstrated (Lee, 2010). Besides hands, body movements are another topic for research. Maidhof et al. (2014) used motion capture with EEG and stated that motions during music performance are bodily adjustments in order to increase the sensory information to play better. Tits. et al. (2015), using motion capture technologies have stated that more trained pianists have better motor control of their hands. Goebl and Palmer's (2013) motion capture experiment underlines the finger movement efficiency in fast tempi and the need for decades of practice. Goebl and Palmer (2008), put forward that the tactile feedback is important for temporal and spacial precision and the findings of Parlitz et al. (1998), using force scan matrix foil support this idea by demonstrating that the amateur pianists applying more and longer force to the keys to achieve the same tempo and loudness. Lai et al. (2008) discovered that piano training should not be considered as power training, but instead, endurance training. Nakamura et al. (2013) designed an experiment with motion capture and EMG to test the effect of daily practice on hands and the results were the reorganization of hand posture and economized muscle work for stiffening joints. The importance of long term practice is also proven in the same work. Their finding showed that it is crucial for learning the upstanding finger posture. On the other hand, Rahman et al. (2011) underline the necessity of having the ability to use either flat fingers or curved fingers when needed. Fast playing is always thought of low musicality but according to Lee (2010) fast playing does not sacrifice other desired musical aims. Also, within the same study, there came a result as biomechanics variables have no effect on maximum tempi. These and similar works are only the beginning of this approach. There is a huge opportunity served by new technologies for discovering the motions behind piano virtuosity.

In today's city life, long hours of music practice is a problem with acoustic instruments since the loud sound may disturb the people living around. Digital technology makes it possible to play the piano with low voice or even with headphones with instruments called digital pianos. The digital pianos have other advantages too, such as being mostly cheaper than acoustic pianos, not needing to have tuned, needing smaller space and also being more lightweight for transport. On the other hand, besides these advantages, they lack some of the most critical aspects of acoustic pianos, which are the touch and the sound. With great improvements in recording and sampling technology, their sound quality is claimed to perfectly simulate the sound of the best concert grand pianos. However, the word perfect is a bit suspicious here since the beauty of the real comes from imperfection also. Digital pianos lack noises and interactive resonances of various parts of the piano, which can be tolerated, but the main problem with them is their touch. Also, there is a digital piano model with the same acoustic piano action but without strings. Instead, the sound produced by the microprocessor which is triggered by the sensors in touch action. Of course, such a design lost its low cost and lightweight advantages considerably. Scientists, who are trying to model the function between the movement of the key and the sound work intensely in this field. Sets of differential equations of first and second-order have been published but the calculation times are inoperable to use for a digital piano. The processing times required given in published work are four hours (Berghe et al., 1995), 75 minutes (Izadbakhsh, 2006) and 28 minutes for flexible hammer shank, 16 minutes for rigid hammer shank (Masoudi et al., 2009). Although the needed time can be seen as decreasing, these models have lots of reductions within. Each piano key has 13 contact points, and each of them exhibits different characteristics. Detailed constitutive responses of organic materials such as felt, wood and leather are hard to be enclosed in a mathematical model. Furthermore, a group of scientists are trying to define and build a haptic feedback loop mimicking the one experienced while playing acoustic piano. In a work by Galembo (2001), piano teachers could identify pianos when they become blind and deaf as a need of the experiment while couldn't differ them when they only listen to the sounds of these pianos. Goebl et al. (2014) implied that the haptic clues are crucial for pianists and piano playing. Some of these clues are the sounds themselves, mostly being the sounds in the bass spectrum with their larger wavelengths while some others are feedback signals from the touch action as a result of keys' inertial, frictional, weight and distance properties. These properties must be felt because according to O'Modhrain & Gillespie (2018) the human body is backdrivable and the secret of well playing may lie behind this interdependence.

On a similar but different basis, force sensors can be installed under the keys (front rail) though it is not easy because of the need for manipulation of the structure of the keyboard. This way, the forces applied to the keys by the fingers can be measured but in pressings not touching the keybed, these sensors can not produce data. In the experiments of Parlitz et al. (1998), 5 players who had spent 4 hours on piano each day from their 6 and 10 years old and 5 amateur players who spend less than 1 hour on piano each day participated, where measurements had been conducted with a force sensor installed under the keys. The expert players are observed to relax their playing fingers immediately after each touch, whereas the amateurs are seen to remain tense for much longer. Furthermore, the forces of the expert's non-playing fingers were found to remain below the resolution of the measurement tool (2 newtons), whereas the amateur's first and second fingers reveal a massive waste of forces. Amateurs used substantially greater and longer force on the keys to achieve the same speed and loudness, resulting in higher mean pulses per touch. In both expert and amateur pianists, pulse and duration values increased as finger coordination demands increased. Similarly, Patterson et al. (2011) used force sensors to compare forces of small hands and large hands for different intervals and showed that as long as the interval gets bigger small hands have more difficulty to obtain the same force as the big hands can apply.

The general experiment setup includes a MIDI data recording too. MIDI is the acronym of Musical Instruments Digital Interface and provides data of onsets and offsets of keypresses with average velocity information (Maidhof, et al., 2014). This velocity data has a 7-bit resolution in most digital pianos but there are digital pianos that support 8 bits of data measured directly from hammers (McPherson, 2013). It is really beneficial to synchronize motion capture data with MIDI but the main constraint of MIDI is its discreteness. In an experiment, EEG (electroencephalography) is used to measure brain activity during a piano performance and in order to synchronize music with EEG data, MIDI data is recorded at the same time (Zamm et al., 2017).

Instead of MIDI, McPherson (2013) developed an alternative system that can measure the movements of keys continuously. It is based on an optical measurement system that can be installed on any piano in order to gather information like MIDI, but unlike MIDI output, this system provides time-continuous velocity function of the key enabling broader observation opportunities when it is synchronized with motion capture data.

As music and its production are phenomena unfolding over time, methods with a high temporal resolution like EEG (Electroencephalography) or magnetoencephalography (MEG) are particularly suited for music performance research. In addition, the EEG method requires participants only to wear an EEG cap, and experiments can thus be conducted in more comfortable situations but MEG is a more difficult method to get data from a pianist because of the need for sitting inside the MEG machine. But to work with EEG, participants can sit in front of a keyboard (Maidhof et al., 2014). There are salient research on musical performances using EEG such as the neural correlation of feedback processing during the performance of scales, fingering exercises, simple error monitoring during piano performance in highly trained musicians, error monitoring in musicians with focal-task-specific dystonia and the neural correlation of ensemble performances (Maidhof et al, 2014). Unfortunately, movement-related artefacts pose a serious problem for EEG recordings. The electromyographic (EMG) activity of mainly the head, neck, and shoulder muscles can be picked up by the EEG sensors and thus the recorded signal can thus be a mixture of brain-related signals (electrical brain activity) and several classes of non-brain-related artefacts, such as the electrical activity of muscles, eye movements, cardiac artefacts etc. However, according to Maidhof et. al (2014), several approaches allow researchers to deal with artefacts, such as preventing excessive head and neck movements of pianists, averaging and filtering the signals and independent component analysis (ICA). ICA is especially effective in separating artefacts such as muscle and eye movement from the EEG data (Jung et al., 2001 as cited by Maidhof et al., 2014).

According to Parlitz (1998), experimental evaluation for rational assumptions of advanced piano playing that are motor programs optimized to achieve the highest accuracy with minimum effort was not made until today. Rahman et al. (2011) underlines the necessity of measuring the dexterous finger movement of pianists while playing although it is very difficult to measure the finger bones, which are very complex. Beyond that complexity, each individual person has different hands. But these differences are all about ratios. The working structure of hands and bodies are mostly the same. Each hand has twentyseven bones and nineteen joints with differing length and width of bones, tissues, muscles and flexibilities but long time slots of training provide the pianists the ability to use their specific limbs skillfully in order to reach more virtuosity (Tits et al., 2015). It is also stated that trained pianists, either with light and tapered fingers or with chubbier hands, both accomplish the desired tones (Lee, 2010).

There are a vast number of different technologies of measurement systems that can be utilized in investigating pianists' virtuosity such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), near infrared spectroscopy (NIRS) etc. but most of these are hard to be used in an experimental setup including piano playing and far from being affordable and practically applicable due to their principles of operation.

## 2.5 Constraints of Previous Works

In most of the works, the experiment is built around two sets of piano players: expert players and novice players. The differences found between them while doing the same tasks are said to define the properties of better piano playing. The main contradiction of such studies is that there is not a real and precise definition of expert pianist. Most of the works utilize the concept of experience as expertise, some of them adds diplomas taken and also some of them adds competition winners into groups but most of them doesn’t ensure that their expert group are the true reference of proficiency at specific skill in piano playing. Though, even winning competitions is not a guaranteed way of becoming a concertist pianist. Even if being a concertist pianist is deemed to be the highest degree in piano career, it is obvious that not all of them are technically equally powerful. Even the virtuosity was meant to be different in the 19$^{th}$ century than in the middle of the 20$^{th}$. Most of the famous pianists of today have fallen behind a subset of pianists who are technically successors of 19$^{th}$ century virtuosity. So the skills of expert pianists who participate in the experiments are not a very trustworthy basis in order to test the relevant hypotheses.

There is also the fact that research on this area has been conducted principally by physicians, engineers, technically-skilled people but not so much with the collaboration of advanced pianists. So the hypotheses and experimental designs that have emerged are mostly located at the beginner level of piano playing. Also, as a result of specialization and communication deficiencies among these people and pianists due to various reasons as aforementioned, the hypotheses used in experiments are mostly limited to very basic skills of struck or pressed touch, handling resistance in keybed and timing in repetition.

For measurements inside the acoustic piano, there comes another constraint: limited space to install sensors that are the tools to quantify piano playing. As a result, most of the experiments have been conducted utilizing single keys, at most non-consequent two keys. On the other hand, EMG, motion capture etc. systems interfere with the piano playing experience by installations to the human body which changes the perception of the player in terms of both comfort and playing feedback.

# 3. METHODOLOGY

Whether they are a piano teacher or virtuoso pianist, their natural ability of playing the piano can not be put into words easily. But all of them feel what they do in their body. There is one thing that shares these feelings other than the pianists: The piano itself. According to Newton's 3rd Law there is an equal and opposite reaction for every action among interacting bodies. Although pianist can not define their skills, the keys which the pianists touch to play music can tell what they experience in terms of numbers gathered by sensors installed onto them.

There are numerous videos of past great pianists and each day new audio video materials of other great pianists are recorded. What if they have force and displacement data of the keys played synchronized with audio and/or video data. This way, their artifice will become immortal to investigate, analyze, replicate and create. Technology is the only tool which has potential to advance cumulatively in life and in piano playing particularly. There is a necessity to develop a measurement system in order to document piano playing better than ever.

## 3.1 Advantage of Measuring the Input Instead of the Body and the Output

One of the important points of measuring piano playing is deciding what to measure. The answers to this question can be grouped in three categories: the human body, the input into the piano and the output of it. Body, in terms of piano playing, means primarily fingers, hand, wrist, forearm and elbow. But shoulders, head and abdominal muscles can be topics of this kind of research also. On the other hand, measuring the piano consists of quantifying the input and the output. Input -for the sound generating mechanism- is the movement of the key with its consequences that are moving inner parts and flying hammer. The output is the momentum of the hammer hitting to the strings and the generated sound (power). As the same playing (the output) by totally different physiologies (the body) achieving same (or at least some qualifyable) high level of skills with standardized pianos can be observed, there appears a need of measuring the input. Under the necessity of determining the input, which is chosen as the important parameter to be concentrated on, the input is the energy transfer trajectory to the piano key by the player. At the first glance, the input is the simplest aspect of piano playing. Indeed, sufficiency of just touching the keys in order to be played seems extremely easy if it compared to string and wind instruments. But it is possible to encounter with (almost) same outputs via very different inputs in piano. The output occurs at the instant that the hammer hits the string but the input is not a single value but rather a continuous function compared to the duration of the "hit of hammer" on the time scale. The shape of the applied force function of the traveling key can unveil different pressing characters of various pianists.

### 3.2 A New Sensor Design for the Piano

There are mechanical (acoustic) pianos produced with sensors installed on by default. The purpose of that kind of production is to get output data (MIDI) from each keypress to produce sound by synthesizer or reproduce the playing of pianists by selonoid motors installed under each key. They create data similar to single MIDI value for each keypress, with the help of their gradient transparent panels and laser beam transmitter/receiver systems under each key. But this technology is incapable for investigation of forces applied to keys and are tracking the "response" of the key rather than the "action" on it.

So developing a new data collecting system to unveil characteristics of virtuosic piano playing is regarded as compulsory to the author. Loadcells are force detecting units widely used in industry with various different shapes and sizes. They are metal blocks which sensors called strain-gauges installed within. Strain-gauges are highly sensitive sensors that can form a circuit which provide proportional voltage values due to micro changes of length on the surface they attached on. So, the core of this work is transforming piano keys to loadcells which are force transducers and gathering data about pianists' touches. But before that, it is necessary to explain how the piano mechanism works.

### 3.3 How the Piano Mechanism Works

According to Nelson (2008), the basic piano mechanism design has been accepted as the structure that transfers the movement of the pianist to the strings most efficiently. While the design of the piano mechanism has changed over the centuries, the basic design hasn't changed much over the decades. Although many piano manufacturers have made minor adjustments to the geometry of the mechanism, the mechanism topology is mostly similar. This is even more true for grand pianos. So much so that there is more variety in upright pianos.

The force applied to a piano key is transmitted to the felt-covered hammer, which strikes the strings and generates a specific sound. A piano action is made up of seven rotating bodies with parallel axes and felts at contact zones. The hammer flies free from the mechanism just before it makes contact with the string, rebound freely and the string continues vibrating. In order to transfer the desired movements, the action's interconnected bodies must meet geometric and dynamic specifications. Contact surfaces lined with felt provide the connection between distinct bodies, allowing for a softer feel and reducing mechanical noise in the motion (Thorin et al., 2013; Masoudi et al., 2009).

As seen in the Figure 3.1, the piano key is like a seesaw with a balance rail pin (44) in the center (Ruthledge, 2006). When the key is pressed, the other end of the key goes up and at the same time the wippen (24) also rises via the capstan (42) screwed to the key. The wippen (24) raises the hammer shank (7) as the jack (31) pushes the hammer knuckle (20). As a consequence of this movement, which the key transfers to the wippen (24), the hammer (6) moves faster, hits the strings (1) and returns. Due to the let-off button, the tip of the jack (31) is freed from under the hammer knuckle (20) before the hammer (6) hits the strings (1). The hammer (6) that returns after hitting the wire is caught by the backcheck (15). This prevents the hammer shank (7) from falling into hammer rest (16) and then bouncing off and hitting the strings (1) again and making an unwanted sound.

Grand pianos have the repetition lever (19) as part of the wippen (24). Repetition lever (19) makes possible the fast repetition of notes. Because of its springs, the repetition lever (19) provides an opposite force between the wippen (24) and the hammer (6). After the key is released, the backcheck (15) releases the hammer (6).

The hammer flange (23) inside the wippen (24) pushes the repetition lever (19) up and the wippen (24) down. The repetition lever (19) also lifts the hammer (6) towards the wire, while the wippen (24) presses the back of the key down. As the hammer (6) rises, the hammer flange (23) keeps the jack (31) moving towards the middle of the wippen (24). Now, the jack (31) is repositioned under the hammer knuckle (20) and is ready for another strike. On a well-regulated piano, when a fully pressed key is released 2mm back, the jack (31) moves away from the jet-off button and is immediately placed under the knuckle (20), enabling fast single note repetitions. Patented by Erard in 1821, this system called double-escapement is standard on all grand pianos today (Dolge, 1972 as cited by Salvosa, 2018).

If the drop screw (8) attached to the hammer flange (9) does not stop the repetition lever (19) at the correct setting, the hammer (6) pushed by the repetition lever (19) will strike the strings (1) again. This setting is called the drop. The drop is the hammer (6)'s slight drop after the let-off. This is the second-escapement of the mechanism. The drop screw (8) does not prevent the hammer from hitting the wire if the hammer (6) has accelerated sufficiently, but does stop the upward movement of the repetition lever (19).

Frictions on the center pins of the repetition lever (19) and the jack (31) affect the speed of repetition. While the friction on the center pin of the jack (31) should be low, the friction on the center pin of the repetition lever (19) should be high, especially in pianos with heavy hammers. While this resistance from high friction enables the wippen (24) springs to lift the hammer (6), it should not give the hammer (6) more acceleration towards the strings (1) than necessary. When friction is low on the repetition lever center pins, the spring tension will also be low, so the returned hammer (6) will continue to swing vertically (Igrec, 2013).

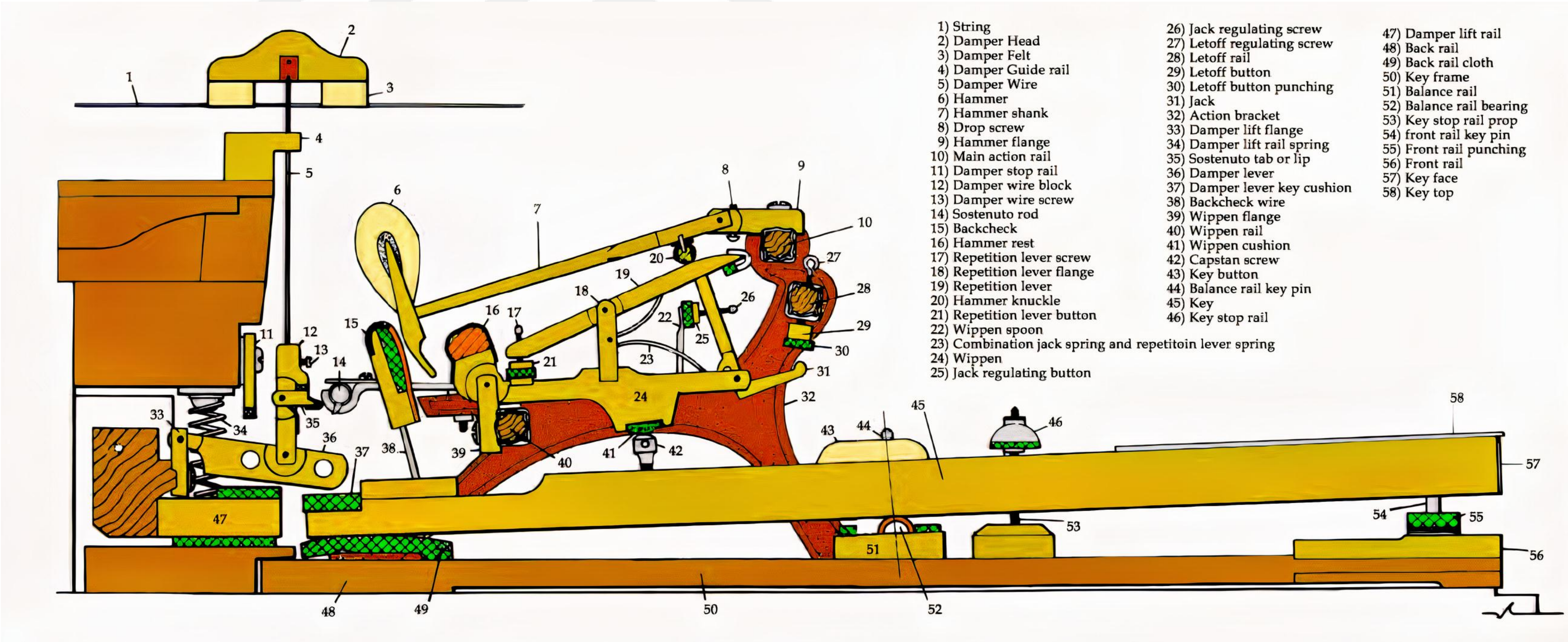



**Figure 3.1 :** Parts of piano action.

### 3.4 Development of the Force Sensor Piano Key Prototype

When a force is applied to one end of an object fixed at the other end, a bending moment develops through the axis and there become axial length changes varying through the transverse cross-section (at fixed axial position) due to the bending effects. As a result of this, tensile and compressive stresses occur on alternating sides of the bent object (called a beam in Mechanics). The internal forces creating these strains can be measured by devices called "transducers" but the main concern for using them is the necessity to modify the original structure to insert the transducer object in between, the possible impossibility to measure quantities for required degrees of freedom and that the costs of the transducers may be high for the budget of the project (Augustine et al., 2016 as cited by Kutlu, 2017). Moreover, the response of the modified structure may considerably deviate from that of the original under expected operating conditions, which makes the measurement process meaningless. In such critical conditions where the integrity of the system is of utmost concern, the object of interest can be instrumented on itself and it can be converted to a transducer itself. Normal strains on material due to externally applied loads can be captured by the strain-gauges applied on the object, in such a specifically located way that by processing their outputs, the applied loads can be derived (Wickham et al., 1995 as cited by ibid).

#### 3.4.1 Strain-gauge theory

Strain-gauge is a sensor for measuring unit length changes that occur on the surface of an object. It is a conductive wire embedded in an insulative medium and bonded on the material of interest. The length of the electrically conductive wire of the strain-gauge sensor changes due to the deformations of the surface it is glued on and as a result of this, deformations can be measured indirectly by changes in gage resistance (Kutlu, 2017).

Taking the resistance of the wire as the bases point, it can be stated as in equation 3.1

$$R = \frac{\rho L}{A} \tag{3.1}$$

where, R is the resistance of gauge (wire) in Ohms, ρ is the specific resistance (material property) of the wire material (Ohm / meter) and A is the cross-section area of the wire in strain-gauge foil.

Since the measurements by gages are based on recording differences between a reference unloaded (here untouched) and loaded (touched) states of the key, the variations over nominal gauge resistances are of interest. Following the usual approach in Mechanics and Experimental Stress Analysis, after some differentiation and linearization of the equations, as in the equation 3.2 the important relation in Strain-Gauge measurements are obtained

$$\frac{\Delta R}{R} = K\varepsilon \tag{3.2}$$

where $\Delta R$ is the change of gauge resistance due to strain applied $\varepsilon$ and K is the proportionality coefficient of gauge (called the Gauge Factor). The recording of strain-gauge signals are handled by digital computers, so the micro-ohm level variations in gage resistance should be converted into electric voltage value. This is handled by a circuit called the Wheatstone Bridge. As seen in Figure 3.2, the bridge can be composed of 1, 2 and 4 active gages depending on measurement principle, called quarter, half and full bridge cofigurations respectively (Molimard, 2016).

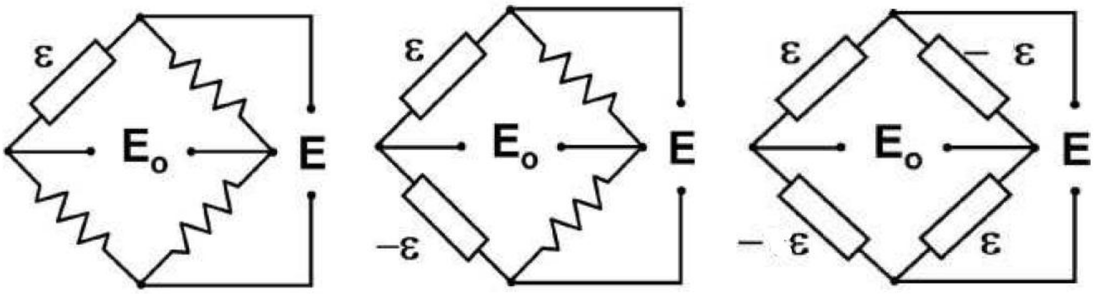



**Figure 3.2 :** The Wheatstone bridge and quarter, half and full bridge connection options for beams.

The most common connection type for experimental stress analysis is Quarter Bridge, while for transducer design the Half or Full Bridge is preferred for improving measurement acccuracy and stability. For beam type structures, in equation 3.3 the output of the Quarter Bridge is

$$\frac{\Delta U}{U} = \frac{K}{4}\varepsilon \tag{3.3}$$

where $\Delta U$ is the measured voltage change over a Wheatstone Strain Gauge Circuit powered with nominal voltage U, and $\varepsilon$ and K are as above. In equation 3.4, for half bridge, with opposite signed gages, this reads as

$$\frac{\Delta U}{U} = 2\left(\frac{K}{4}\varepsilon\right) \tag{3.4}$$

and in equation 3.5, for full bridge under same principles as

$$\frac{\Delta U}{U} = 4\left(\frac{K}{4}\varepsilon\right) \tag{3.5}$$

which all relate the applied strain to a voltage difference that can be recorded to a computer through an ADC (Analogue-to-Digital Converter) (Molimard, 2016).

On the other hand, as bonding gage on an elastic body, deformations of the conductor are thus fixed to strains of the elastic body and measured as stated above. For example, as in Figure 3.3, in a cantilevered simple beam subject to bending via a tip load, equation 3.6 can be derived for applied tip force-axial strain relationship (which is, in fact, linear for conventional materials and almost-rigid small deformation structures)

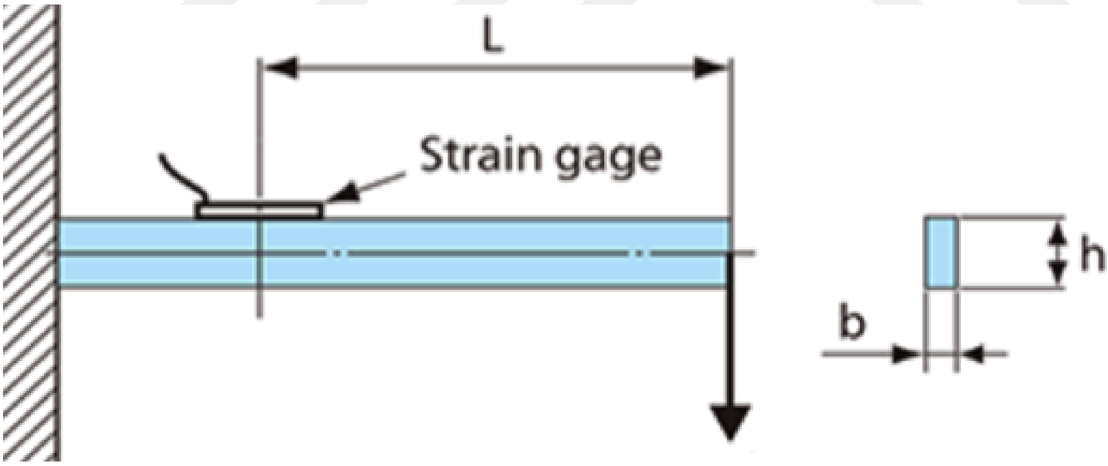



**Figure 3.3 :** The bending model of a cantilever beam.

$$\varepsilon = \frac{1}{E}\frac{Mc}{I} \tag{3.6}$$

which can be expanded in equation 3.7 as

$$\varepsilon = \frac{1}{E}\frac{(F\ L)(\pm\frac{h}{2})}{\frac{1}{12}b(h)^3} = \pm\frac{6\ (F\ L)}{Ebh^2} \tag{3.7}$$

where the terms read as,

$\varepsilon$= the axial strain values read from strain-gauges (+ on top, - on bottom, for the case shown in Figure 3.3)

E = Young's Modulus (Modulus of Elasticity) of the beam material

M = Internal Moment at the cross-section of beam (piano key) where the gages are installed

F = Tip force applied

L = distance of point of force application to the strain-gauge

b = width of the beam (piano key)

h = height of the beam (piano key)

c = Distance from beam longitudinal axis to top/bottom surface

I = Second Moment of Area of Beam Cross-Section

moreover, strain at a point on a structure is not only one single number. Based on the direction of interest at a fixed location and the type of stressing that occurs at the point of interest, shearing and normal strains may exist. Strain-gauges can be used only on free (untouched) surfaces on an object, where exactly two-dimensional stress state occurs. Therefore, only $\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}$ (i.e. in-plane) strain components exist. Since strain-gauges are only sensitive to normal strains (i.e. length changes) but shearing is based on angular deviations, the in-plane strain state ($\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}$) can be obtained at the point of interest via measuring normal strains in 3 mutually independent directions (Sciammarella & Sciammarella, 2012). As shown in equation 3.8, stating in other words, strain at a point in a preferred direction defined in a fixed axis system is a function of the 2 normal strain components and the in-plane shearing angle namely $\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}$ in the form

$$\varepsilon_{\alpha} = \varepsilon_{xx} \cos^2(\alpha) + \varepsilon_{yy} \sin^2(\alpha) + \gamma_{xy} \cos(\alpha) \sin(\alpha) \tag{3.8}$$

which is a linear transformation of $\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}$ (Sciammarella & Sciammarella, 2012). So the piano key should be transformed to be able to make experimental stress analyses in order to calculate the forces applied by pianists during playing.

### 3.4.2 Definition of the problem

The problem of converting the piano key into a sensor which can provide meaningful outputs goes through the steps of

1. Generating a Mathematical Model
2. Replicating the Key Geometry
3. Making necessary modifications to base geometry
4. Instrumentation on the key itself
5. Planning the calibration procedures (if necessary)
6. Planning of auxiliary instrumentation
7. Cabling and data acquisition
8. Data processing from recorded data

So it can be deduced that the procedure will include several steps, each one having its own characteristic and challenges. This includes 3D Modeling of the key prototypes, providing assumptions on applied loads and relevant parameters of the piano key, finite element analysis (FEA) for determining strain-gauge locations, conducting virtual experiments to check the applicability of the concept, the reproduction of real piano keys based on the virtual design, keeping the basic mechanical characteristics as close as possible to original keys (moment of inertia, weight, etc…), the installation of strain-gauges on the reproduced keys and checking physically the outputs of the system, comparing to FEA results (a means of calibration), the replacement of the original keys in the reference piano, experimental data collecting with a computer connected to the piano that has keys replaced with sensor-installed ones, investigation of signals, applying various signal processing techniques to recorded data and develop ideas to identify estimated parameters. At this stage, based on the efficiency and feasibility of the experimented results the process returned to design iterations and reinstallation of sensors.

### 3.4.3 Generating a mathematical model

The piano keyboard is consisting of 88 keys (commonly), that has a compact layout on the player side, but generates sound by generating an impulse on the side-by-side oriented string system. Each note may have one, two or three (even four for some special designs) strings hit by the same hammer. A general layout of a grand piano keyboard is shown in Figure 3.4. Due to the restrictions on hand biomechanics, such a design is inevitable and thus the piano keys are not completely standardized. Although the sizes of areas which can be touched by the pianists are almost the same over all brands and models of today, the invisible part of the keys behind the open fallboard has slight differences in almost all models and also within different productions of a particular piano model.

**Figure 3.4 :** A sample piano keyboard.

The keys closer to the high-pitch side and low-pitch side have broken axes to enable space for the string layout, though the mid-registers have relatively straight geometry.

### 3.4.4 The piano key mechanical model

A piano key can be regarded as a broken axis beam, with a length-to-height ratio greater than 10:1. The beam can be assumed to be under a dynamic equilibrium during travel and is (almost) under static equilibrium when untouched or deeply pressed.

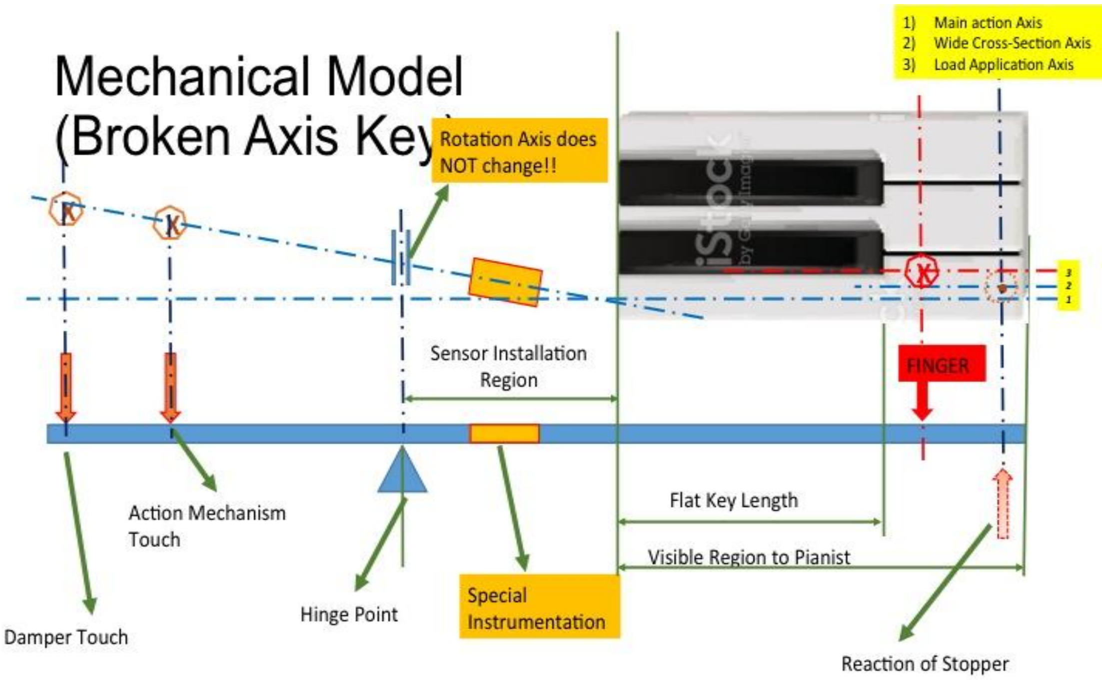



**Figure 3.5 :** Main dimensions (parameters) of a broken-axle key.

According to this parametrization, the dimensions of the piano key used for prototype model 1 in section 3.4.6.1 can be seen in Figure 3.6.

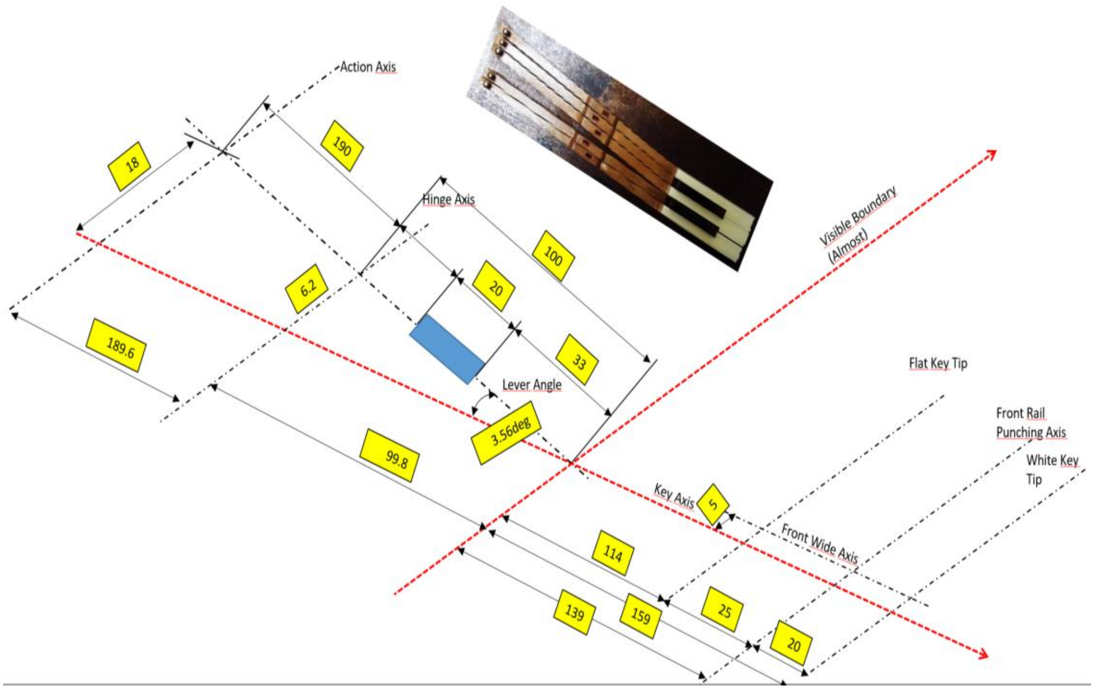



**Figure 3.6 :** The dimensions of the model of a sample piano key (key no 37) from the upright piano Marshall and Wendell 51501 (in mm)

Whether it stands or travels, the beam (key) is hinged at the balance rail pin point, and is moving through a guide at the front-bottom, called front rail pin. Thus, one can state that, for the piano key:

- The vertical motion is like a seasaw over the hinge point
- The motion in the vertical plane is guided by balance rail pin and front rail pin and remains in vertical plane (disregarding the stiffness of the friction elements (key bushings)
- In horizontal plane, the beam (key) is like simply-supported cantilever beam since it is hinged at two points (free to bend)
- Torsional degree of freedom of the beam are fixed at the hinge points due to slider-like contacts, thus the torque is shared among two supports

Based on these facts, the most sensitive region of the beam can be regarded as the hinge point region for the strain-gauge instrumentation around which the loads are balanced. Additionally, it should be noted that the beam model is non-linear due to the contact condition at the front rail side under the finger, since when the key touches the frame at the bottom, the mechanical model in the vertical plane switches to a simply-supported beam overhang with the introduction of the additional support. It is worthy also to note that the dampers and the action mechanism are also transferring loads by contact, but they can be regarded as external loads and do not change the beam's bending behaviour since they do not impose any kinematic restraints on bending characteristics of the key (beam).

As it can be seen in Figure 3.7, there are several loads that act on the piano key. These can be recalled as

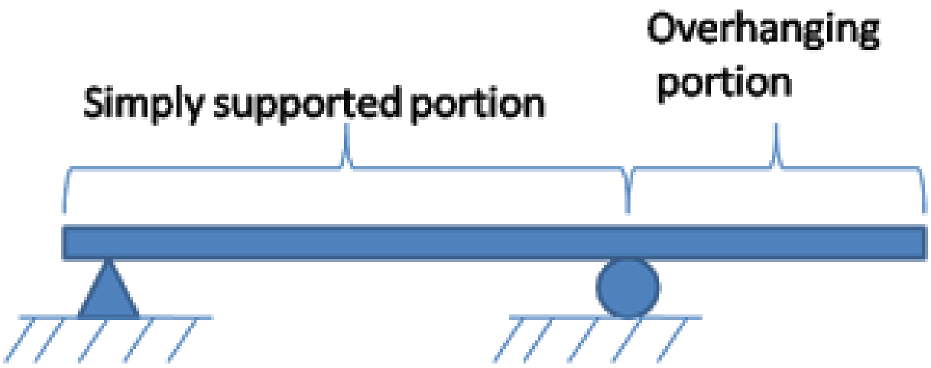



**Figure 3.7 :** A simply-supported beam with overhang.

- The load from the damper that acts in axial and vertical directions at the far end in the piano)

- The load from the action mechanism that acts through a contact further away from the balance rail pin in the vertical direction only (disregarding friction between the semi-spherical head of capstan and the key bushings)
- Loads from the finger of the player on the visible surface
- Reaction load from the front rail punch
- Various friction components at the contacts.

It can be inferred that the friction forces at the interfaces (hinges) will be low compared to loads from action and dampers, since one can precisely feel (by hand) the fluctuations in load in various stages of the keypress and whether the dampers are active (sustain pedal not pressed). Thus, as the first stage of modelling, these loads have been disregarded. By good regulating and maintaining a mechanical piano, this approximation can be transferred with great accuracy to real life too.

The front rail punch (acting as a stopper) itself is active when the key is fully pressed so it is impossible to neglect it. And after the key touches the bottom, a trigger signal or threshold should be generated so that the calculation formulae (i.e. the boundary conditions of the beam model) should be altered accordingly. It is impossible to neglect this detail.

The most important issues are the finger actions on the key – i.e. the touch. The touch of the finger will, in the most general case, generate three load components:

- Vertical load F, due to depressing the key
- Lateral load Y (pushing the keys to left/right from the viewpoint of the player)
- Normal load N (pushing the keys towards or pulling it backwards)

Making everything more complex is that, the point of touch is not the same during playing. It changes on the surface of the key, and even sometimes the player (intentionally or unitentionally) hit the key by the side. The geometric measures of such a layout, that shows the distances of the touch to the key front surface and to the beam axis is given in Figure 3.8.

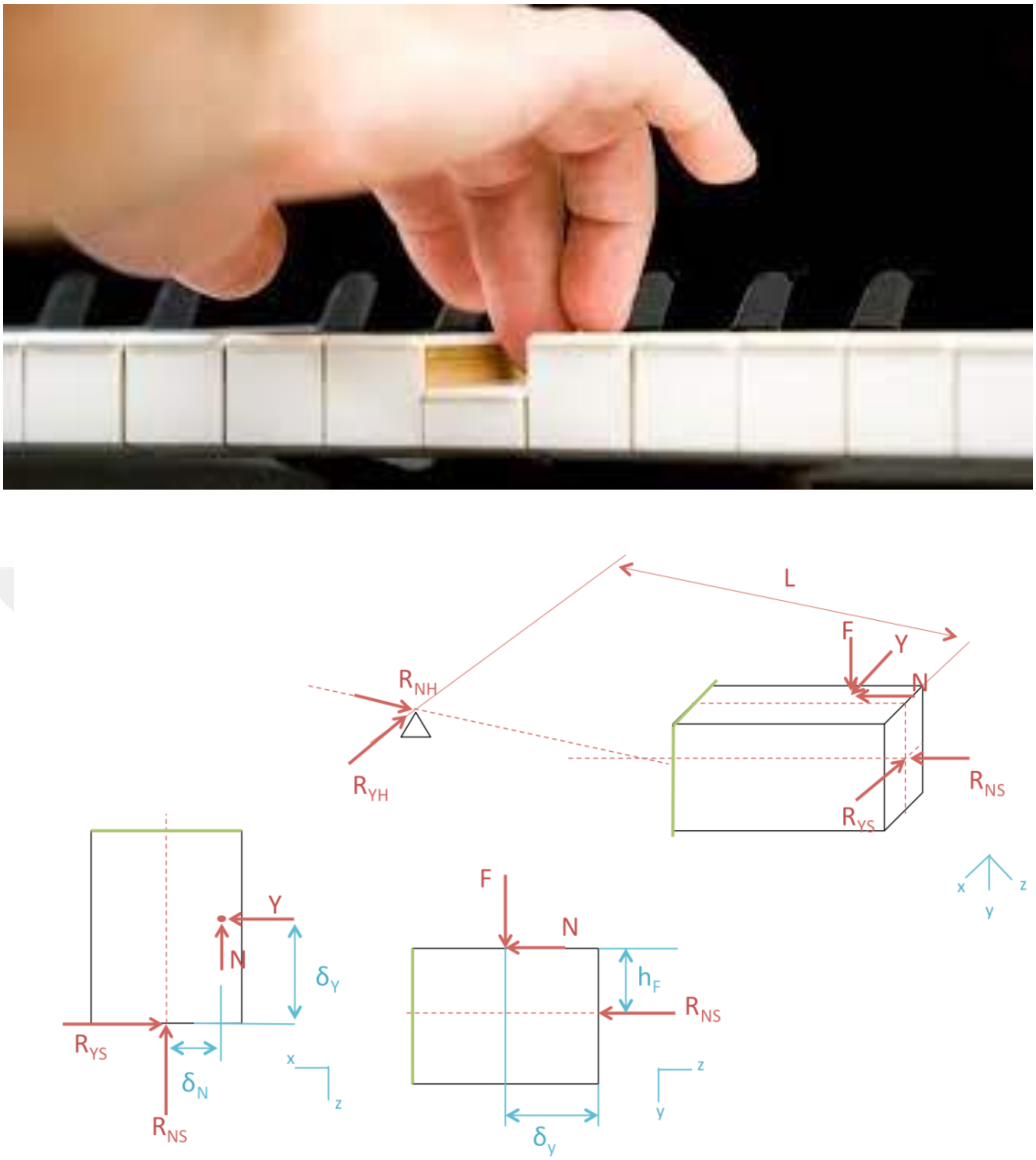



**Figure 3.8 :** The finger touching the piano key and the “touch” model.

In this configuration, the moment about x (lateral) axis is the only free one that can be carried to the hinge point. Effect of N is an overconstrained system, with $N$ being shared between the reactions $R_{NS}$ and $R_{NH}$ with a small contribution to moment due to $\mathrm{h}_F$, which is half the key height. In equation 3.9, since the key is almost a beam, $\mathrm{h}_F << L$ is assumed to hold and for the hinge

$$M_x = -F(L - \delta_Y) + \mathrm{Nh}_F \approx -F(L - \delta_Y) \tag{3.9}$$

can be said to hold, also assuming that N will not contribute to axial strains on the key because most of the load will be resisted at the support due to front rail pin.

The situation is more complex for Y since the load is shared between two always-active hinge points in terms of reaction loads $R_{YS}$ and $R_{YH}$. Assuming Y is always near to the support due to the stopper pin, $M_y$ bending moment on the beam will be very low especially towards the hinge point, also because there are no lateral loads at the overhang region.

Thus, for the rectangular cross section piano key, the combined bending equation 3.10

$$\varepsilon = \frac{1}{E}\left[\frac{F_N}{A} + \frac{M_x}{I_{xx}} y - \frac{M_y}{I_{yy}} x\right] \tag{3.10}$$

at a cross section toward the balance point (i.e. hinge), with enough accuracy, can be assumed to simplified to equation 3.11

$$\varepsilon = \pm \frac{1}{E}\frac{M_x}{I_{xx}}\left(h/2\right) \tag{3.11}$$

while the couplings and emerging torque due to broken axis are not being considered since the cross-sectional warping of a rectangular torsional system is negligible and the dominant straining due to torsion is in shear but the intended measuring direction is axial. This equation (3.11) is the same as the equation 3.6 that has been developed in section 3.4.1.

### 3.4.5 Replicating the key geometry

Instrumentation of keys requires more or less intervention to the original structure. So it is crucial to have replicable models of piano keys that need to be instrumented mainly because to keep the original keys intact so the piano itself, and to satisfy the need for replacement in case of electronic or mechanical failure. The replicable model of the keyboard was initially sought through the market, to find a keyboard directly from some supplier. It has been (surprisingly) figured out that that there is no such a product line (the complete keyset for a piano with a given serial number) for sale in the market.

Thus, having faced the fact that keyboard setup is not offered to the market for exclusively sale, as an initial step, the irregular geometry of the chosen piano keyboard is replicated in a point cloud environment (Figure 3.9) to control against the CAD model dimensioning (Figure 3.10).

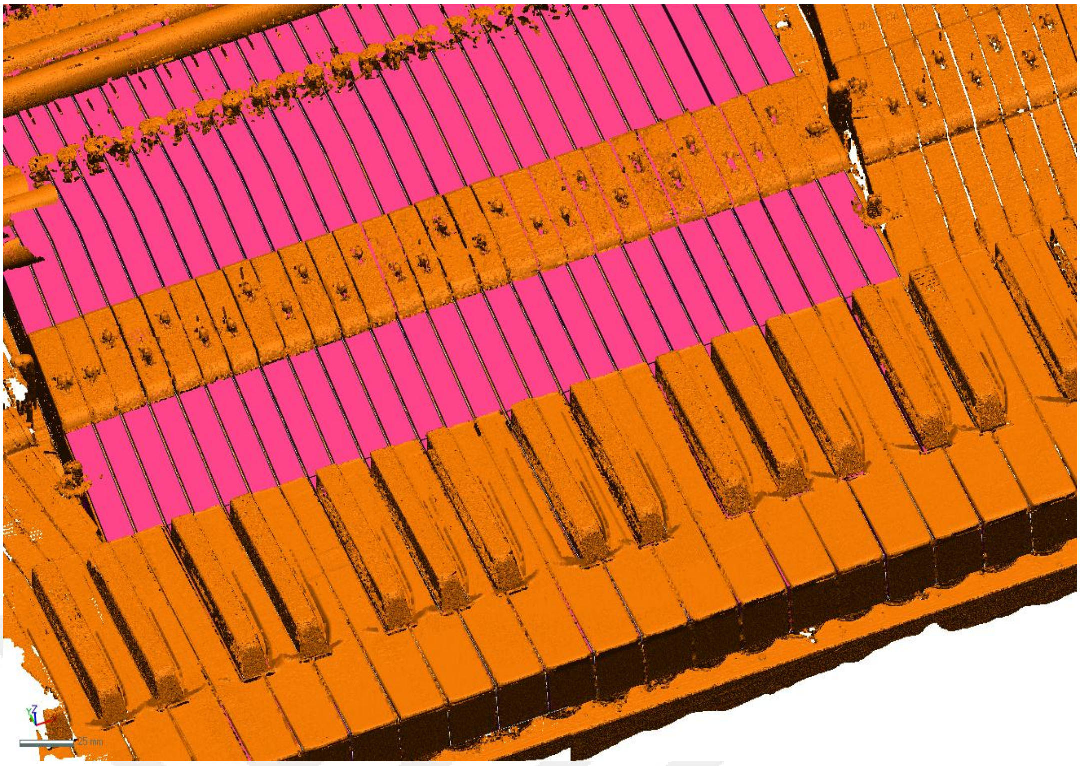


**Figure 3.9 :** Overlaid solid model on point cloud.

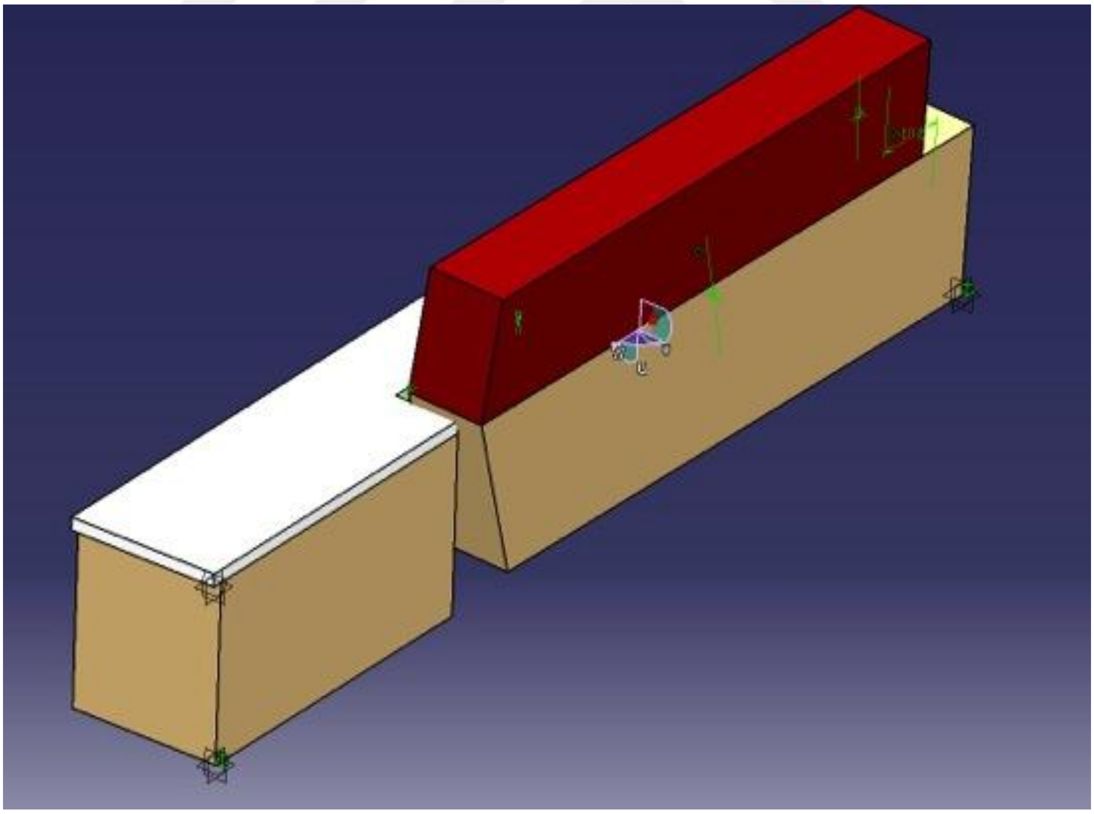


**Figure 3.10 :** Detailed CAD model.

The point cloud of the existing piano key is captured via Faro Arm Laser Digitiser (Figure 3.11). Then the different properties that need to be more exact such as key angles, hole organizations, the width of the white keys measured by hand and solid modelled in Catia Software.

**Figure 3.11 :** The scanning process.

The dimensioning of the keys are following some geometrical periodic rules and tight tolerances are required to keep this periodic structure, which is defined per octave.

The Yamaha C3 keyboard that has been utilized is 165mm per octave (Figure 3.4). This fits into 6.5” / octave main dimension. Following work (Piano Keys, n.d.), the exact dimensions of the keyboard have been developed for the front (Table 3.1, Figure 3.12), and then the known locations of hinges, action interaction point and the damper contacts have been positioned. This resulted in the replicative exact dimensioning which yielded the positioning sketch. The CAD model based on this positioning sketch and the actual scan of the keyboard is overlaid for control purposes in Figure 3.9.

**Table 3.1 :** Dimensions of the keys at the visible region of a Grand Piano.

| NOTE NAMES | REAR | FRONT |
|---|---|---|
| C | 14.02 | 23.32 |
| C# | 13.95 | |
| D | 14.02 | 23.32 |
| D# | 13.95 | |
| E | 14.02 | 23.32 |
| F | 13.56 | 23.78 |
| F# | 13.63 | |
| G | 13.56 | 23.78 |
| G# | 13.63 | |
| A | 13.56 | 23.78 |
| A# | 13.63 | |
| B | 13.56 | 23.78 |
| Total Width | 165.09 | 165.08 |

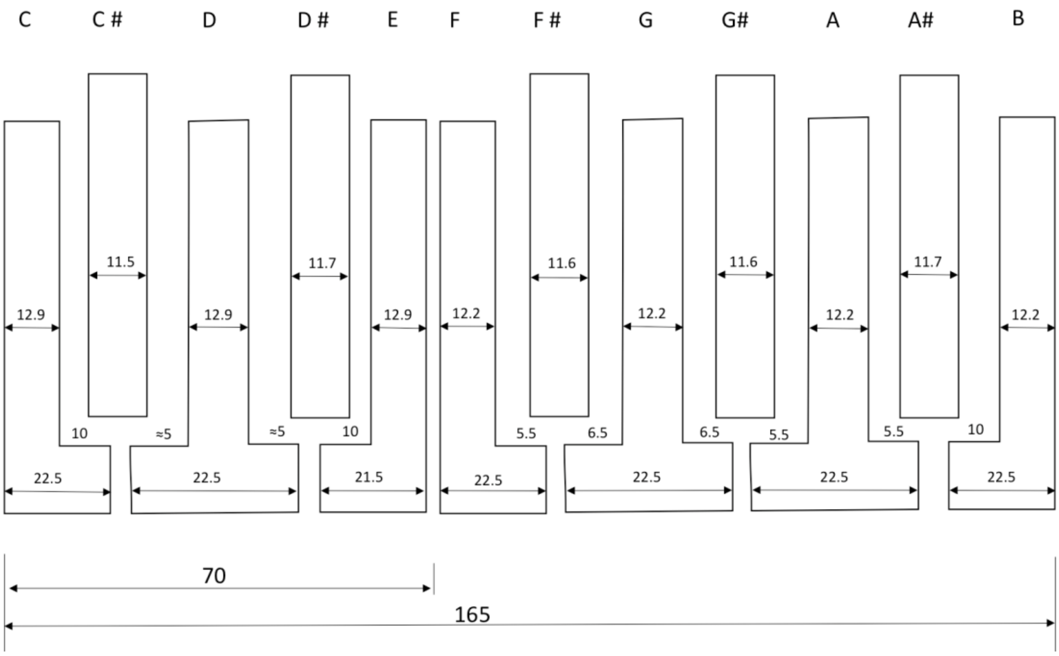



**Figure 3.12 :** The manually obtained main dimensions of one octave.

### 3.4.6 Force transducer piano keys

Strain-gauge instrumentation in order to convert an object to a force transducer have constrainst related to the structural properties of the object. Linear elastic objects have a proportion between the strain and the applied loads and local stresses. Thus, a change in its shape returns to the initial state after the applied forces are removed (practically without any hysteresis). However, as a first iteration to keep the measurement chain remain in conventional application methods on metals with strain-gauges, a minor modification to a “far” point of the key is applied while keeping important mechanical properties (such as stiffness) almost constant (to order of magnitude).

Since bending is the main concern, the bending rigidity of the key after modifications should be similar to that of an original key. In equation 3.11, following pure bending assumption,

$$\Delta\left[\frac{1}{R}\right] = \frac{M}{EI} \qquad (3.11)$$

is applicable, where $\Delta\left[\frac{1}{R}\right]$ is the curvature change, M is bending moment and $EI$ is bending rigidity with E the elastic modulus (Young Modulus) and I the section (Area) moment of inertia. As seen in quation 3.12, for a rectangular cross-section,

$$I = \frac{bh^3}{12} \qquad (3.12)$$

### 3.4.6.1 Model 1 - Initial trial of instrumentation

The first steps of designing a strain gauge installed piano key is taken. This new key is going to collect continuous force data according to applied forces to key during playing.

The initial and more controlled trial was intended on replacing a key section with plates attached to the remaining wooden structure. A view of the design is given in Figure 3.13.

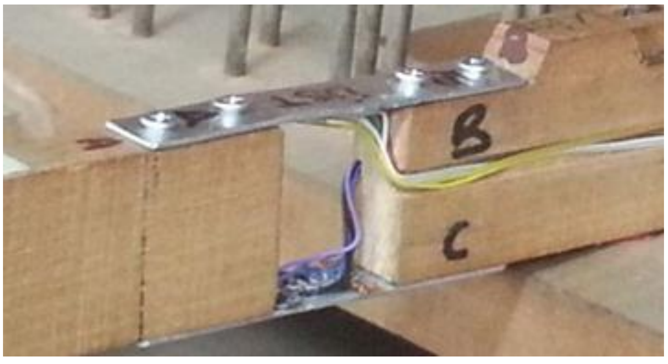



**Figure 3.13 :** Concept of initial instrumentation attempt.

To keep the key stiffness almost equal to the original key, a control calculation should be conducted. A screenshot of example calculation form is given in Figure 3.14, where the bending rigidity of the wooden key is compared to a design with aluminum or magnesium plates on top and bottom. Details of calculations follow the same rules of Mechanics of Materials as stated above.

| Wooden Extracted Block | | | 2 Piece Aluminium Plate | | | | 2 Piece Magnesium Plate | | | 1 Piece Aluminium Plate | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E | 1001 | kg/mm2 | E | 77000 | Mpa | | E | 42000 | Mpa | E | 210000 | Mpa |
| Rho | 0,431 | g/cc | Rho | 2,7 | g/cc | | Rho | 1,8 | g/cc | Rho | 2,7 | g/cc |
| E | 9819,81 | Mpa | E | 77000 | Mpa | | E | 42000 | Mpa | E | 210000 | Mpa |
| Rho | 4,31E-10 | t/mm3 | Rho | 2,7E-09 | t/mm3 | | Rho | 1,8E-09 | t/mm3 | Rho | 2,7E-09 | t/mm3 |
| Rho | 0,000431 | g/mm3 | Rho | 0,0027 | g/mm3 | | Rho | 0,0018 | g/mm3 | Rho | 0,0027 | g/mm3 |
| b | 15 | mm | b | 10 | mm | | b | 10 | mm | b | 15 | mm |
| h | 20 | mm | h | 1 | mm | | h | 1 | mm | h | 3 | mm |
| L | 20 | mm | L | 30 | mm | | L | 30 | mm | L | 30 | mm |
| | | | d | 1 | mm | Embedding of Plate into Wood Carving | d | 1 | mm | d | 1 | mm |
| A | 300 | mm2 | A | 10 | mm2 | | A | 10 | mm2 | A | 45 | mm2 |
| V | 6000 | mm3 | V | 300 | mm3 | | V | 300 | mm3 | V | 1350 | mm3 |
| m | 2,586 | g | m | 0,81 | g | | m | 0,54 | g | m | 3,645 | g |
| | | | Ix1 | 0,8333333 | mm4 | One off, about its own axis (through G) | Ix1 | 0,833333 | mm4 | Ix1 | 33,75 | mm4 |
| | | | e | 9,5 | mm | Distance to main Centroid | e | 9,5 | mm | e | 0 | mm |
| | | | Ae2 | 902,5 | mm4 | Steiner's Theorem | Ae2 | 902,5 | mm4 | Ae2 | 0 | mm4 |
| Ixx | 10000 | mm4 | Ixx | 1806,6667 | mm4 | | Ixx | 1806,667 | mm4 | Ixx | 67,5 | mm4 |
| EIxx | 98198100 | Nmm2 | EIxx | 139113333 | Nmm2 | | EIxx | 75880000 | Nmm2 | EIxx | 14175000 | Nmm2 |
| c | 10 | mm | c | 11 | mm | | c | 11 | mm | c | 1,5 | mm |
| M | 1000 | Nmm | M | 1000 | Nmm | | M | 1000 | Nmm | M | 1000 | Nmm |
| S | 1 | Mpa | S | 6,0885609 | Mpa | | S | 6,088561 | Mpa | S | 22,22222 | Mpa |
| uE | 101,835 | - | uE | 79,072219 | - | Simple Sensitivity Check - Uniaxial Strain Signal | uE | 144,9657 | - | uE | 105,8201 | - |

**Figure 3.14 :** Sensitivity and rigidity comparisons.

The first prototype seen in Figure 3., was worked in a cadaver piano. The results obtained from the first tests were more successful than expected.

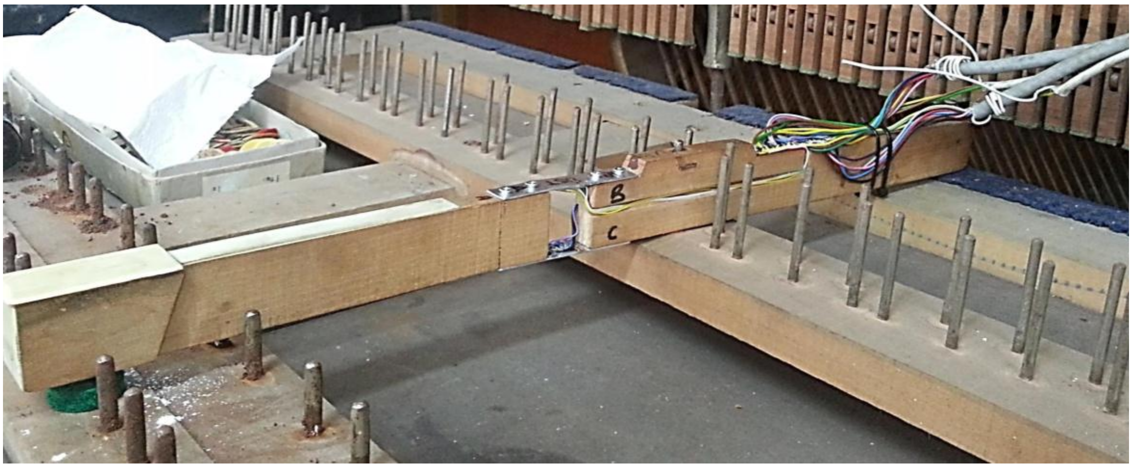



**Figure 3.15 :** Prototype key installed in piano.

One side of the piano key is ditched for the wires coming out of strain-gauges and these wires are fixed in order to prevent damage to them and the solders during transportation, installation and testing.

But the piano itself was not feasible for further work because of the difficulty to find an area of consecutive keys that have precisely working action. Another problem with the first prototype was its durability. The screws were getting loose after continuous testing and this change were distorting the measurements.

The piano, which the sensor-installed key is a part of is a Marshall and Wendell brand upright piano. Its condition is called to be a cadaver piano. Regarding its serial number (51501) its manufacturing date is identified as 1910-1915. ("Pianoage by Serial Number," n.d.)

Close-up views of strain-gauges installed on the aluminium plates can be seen in Figure 3.16. Before attaching strain-gauges to the surface, the area of application is prepared by sandpapering until its smooth. After being sure the strain-gauges are fixed solidly, resistance should be checked. The resistance read in the strain-gauges was 350 ohms and it's in between the values written in the specifications document of Micro Measurements CEA-031CE-350 strain-gauges, with a gauge factor of about K=2.10 (specifications in Figure A.1).

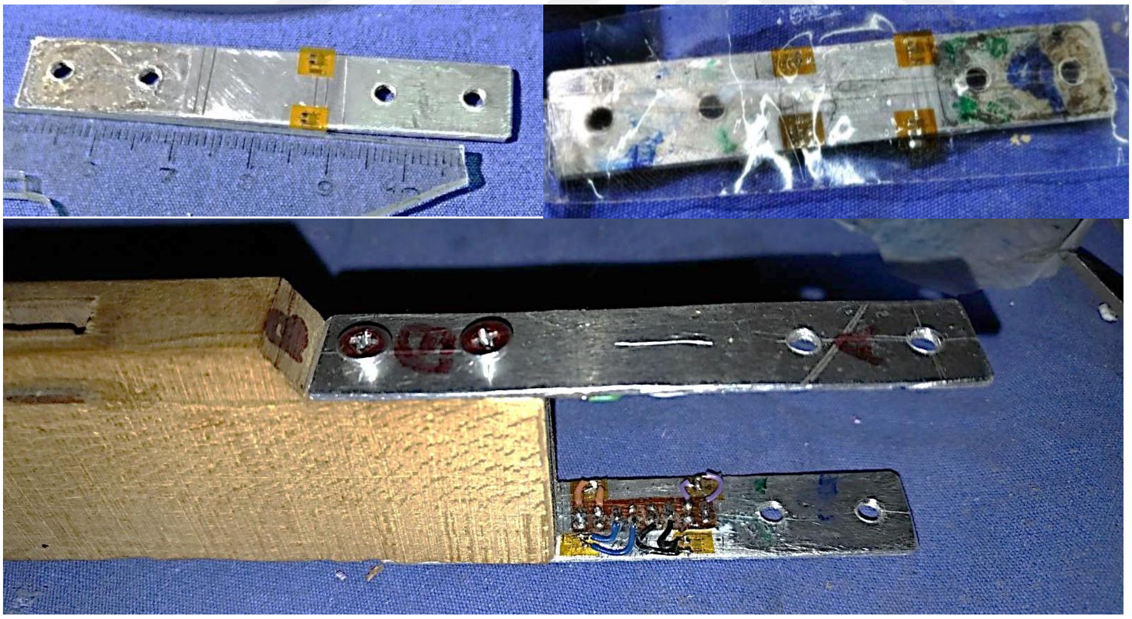


**Figure 3.16 :** Strain-gauge installation process.

Tests done with the first prototype show that the system is working efficiently. Just one key is sensored. The data collected at initial attempts, could show different force profiles applied during different playing techniques like, struck, pressed, *legato* and *staccato* touches distinctively.

When playing piano both struck and pressed touch techniques must be used. Struck touch is starting to move the finger above the key surface so there becomes an impact and sudden acceleration of the key in the touch instant as in the Figure 3.17 top. On the other hand, pressed touch is being contacted with the key before the movement begins. So the pianist can increase the force to the key gradually and the slope of the curve in Figure 3.17 bottom demonstrates this.

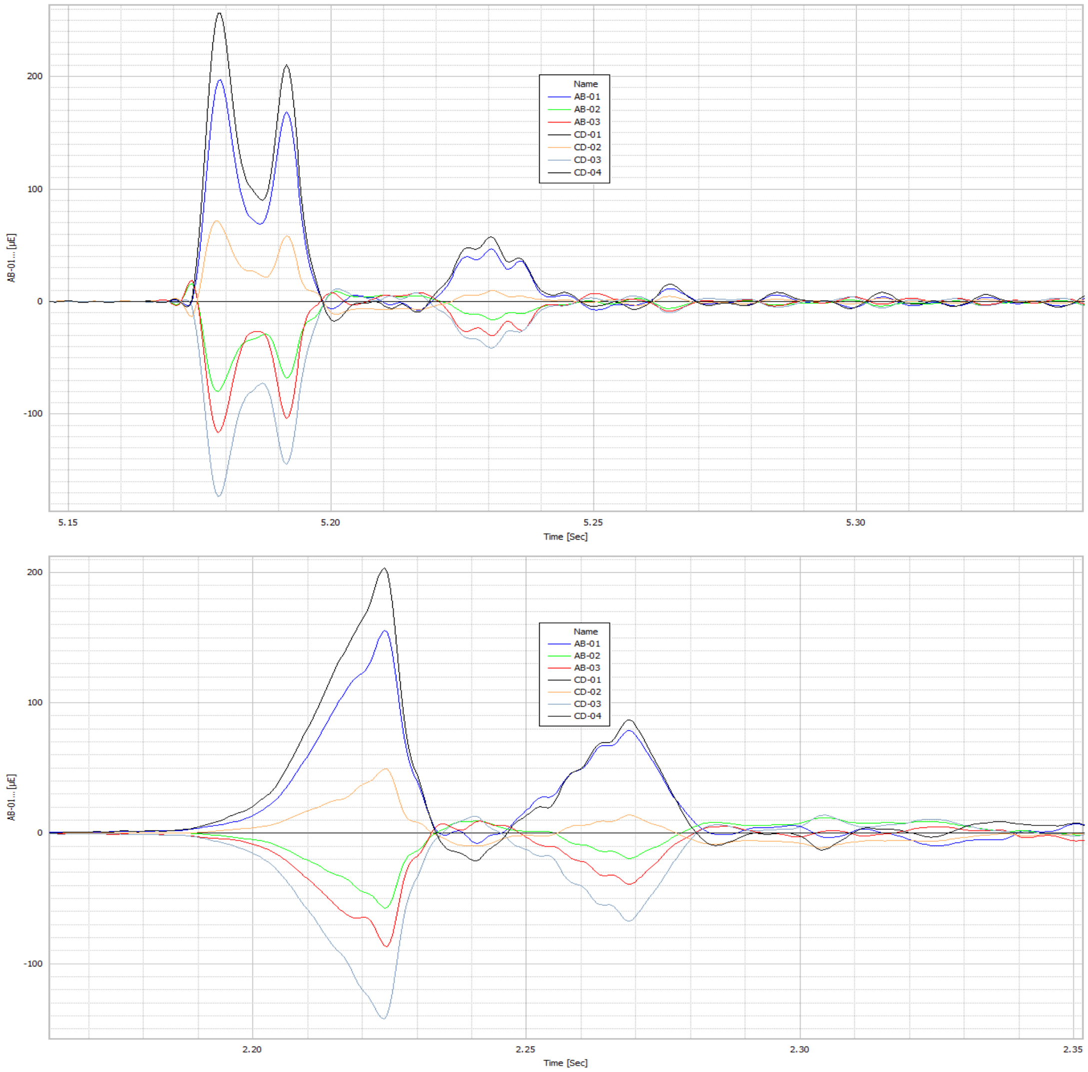



**Figure 3.17 :** Struck touch (top) vs pressed touch (bottom), all gages overlaid.

The graphics obtained by the tests comparing *staccato* and *legato* repeated note techniques are shown at Figures 3.18 and 3.19. Both figures have graphics of repetitions at the top and magnified single key press at the bottom.

Repeated notes created more complex force curves than the single notes, especially the *legato* touch. The aim of *legato* playing is to create an imitation of the continuation of the sound as if it's violin or human singing. Because of having decay in each of the piano sounds, the players use special techniques as playing the notes in series in the middle of key's travel distance, using middle-middle playing according to Mimaki's (2010) categorizations, holding the previous note while pressing the key, using slightly pressed damper pedal, shaping of wrists and similar.

As seen in figure 3.18, *legato* playing sustains the various forces upon the key. This is consistent with the definition of *legato*. The sound shouldn't decay so the forces are.

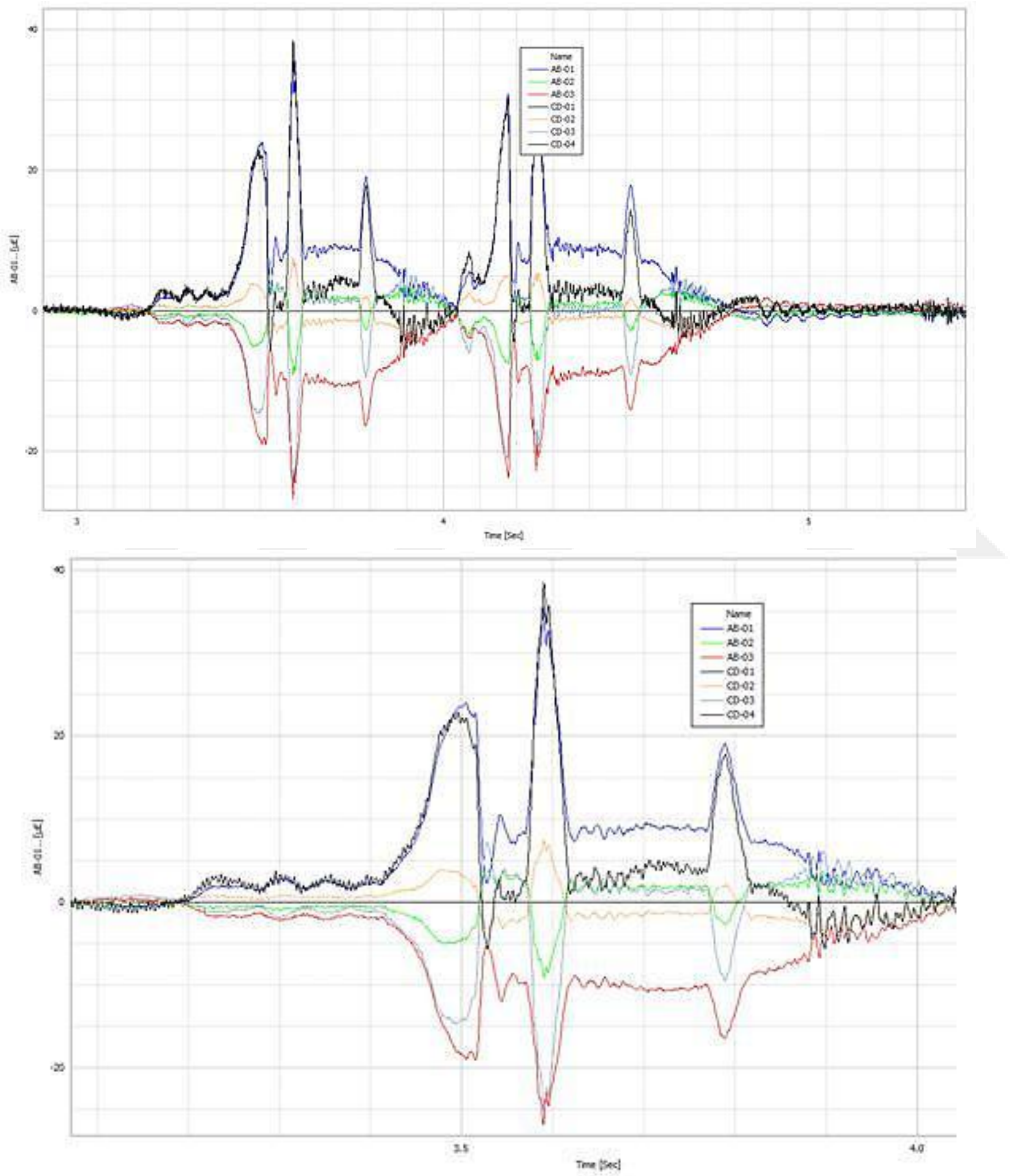



**Figure 3.18 :** *Legato* repetition, all gages overlaid.

As shown in Figure 3.19, the *staccato* touch has bigger leaps at its force-time function. While there are different ways to play *staccato* as finger, wrist, elbow *staccato*s, all of them have stopping the applied force to the key almost immediately after the sound occurs in common. The behaviors of the strains measured by the strain-gauges decrease in a short period of time when it's compared to other profiles. So, *staccato* and *legato* touches can be observed at the time domain through the values obtained by strain-gauges.

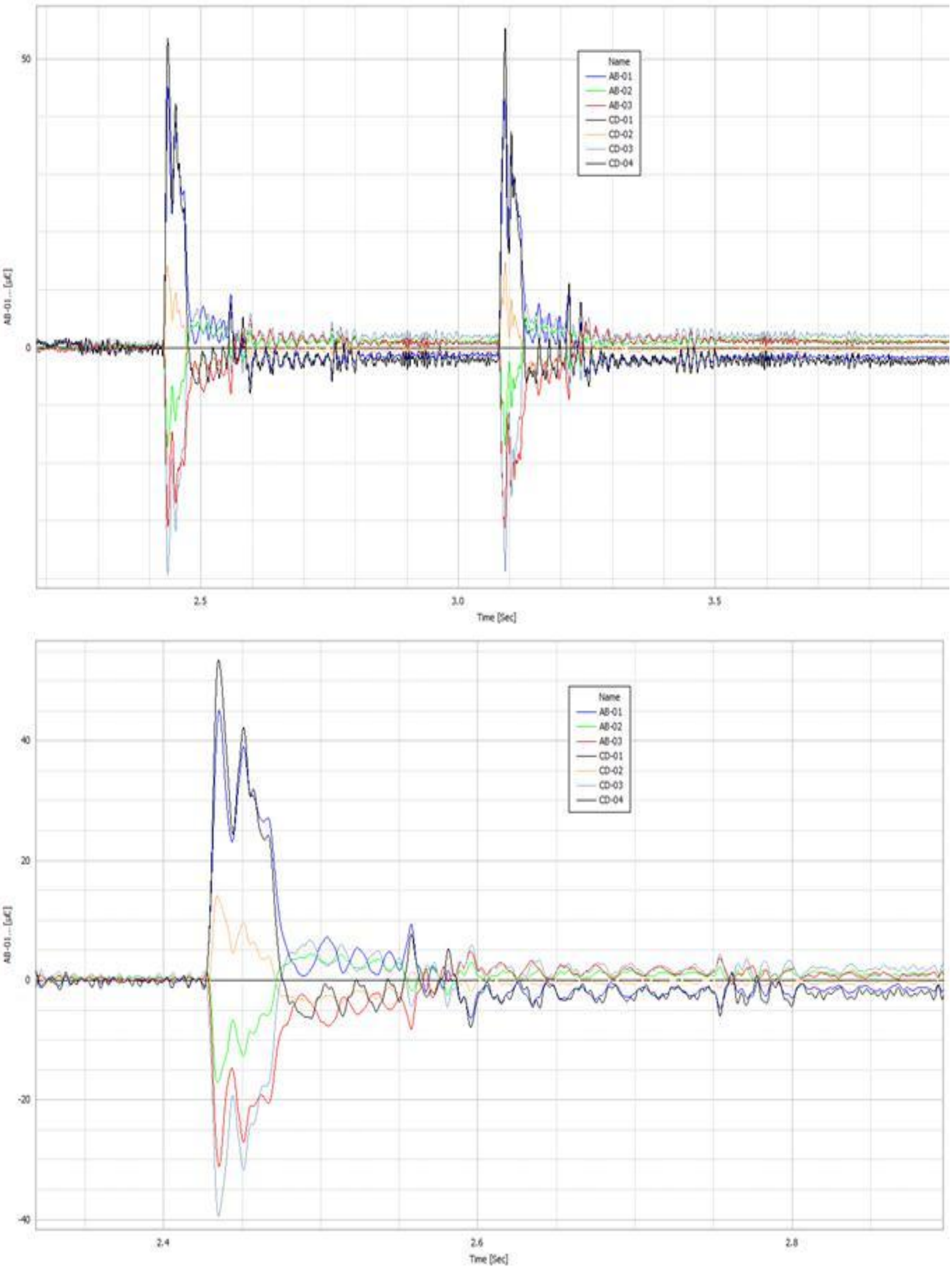



**Figure 3.19 :** *Staccato* repetition, all gages overlaid.

The observed drawbacks of this method have been identified as follows:

- Lack of stability – there was recorded vibrations on the key. Though the sensitivity and stiffness were comparable and of satisfactory levels, the dynamics of the key was altered and significant transient vibrations have been observed due to the impossibility of tightly coupled installation.
- Lack of precise positioning - The installation and cabling were not so precise, which, when a sequence of keys would be lined side by side could result in installation problems. Also, with minimal intervention, especially lateral stability would be a problem. This would require even greater number of keys to be produced until a successful layout would be established, if any.
- Space requirements – The keys that the trials had been conducted on was much larger than that of a grand piano, providing enough space for installation and cabling. However, with grands, this space availability is not so abundant but very limited.

#### 3.4.6.2 Model 2 - The second prototype

The problems that have been aforementioned yielded the process of generating an alternate design, with a completely engineered sensor region to be produced outside and installed within the key material.

The second prototype seen in Figure 3.20 developed under the need for a more durable design. The aluminium piece is designed in digital domain regarding the elastic properties of the wood. It seemed a solid solution because of its easier operation for instrumentation and installation.

To have a better understanding of the strain-gauge localizations, numerical methods have been utilized after a design has been generated.

Finite elements analysis is mainly a numerical method for solving partial and ordinary differential equations and/or equation systems. The ease of applicability and the vast number of practical aspects to elasticity problems makes it a popular tool for engineering analysis.

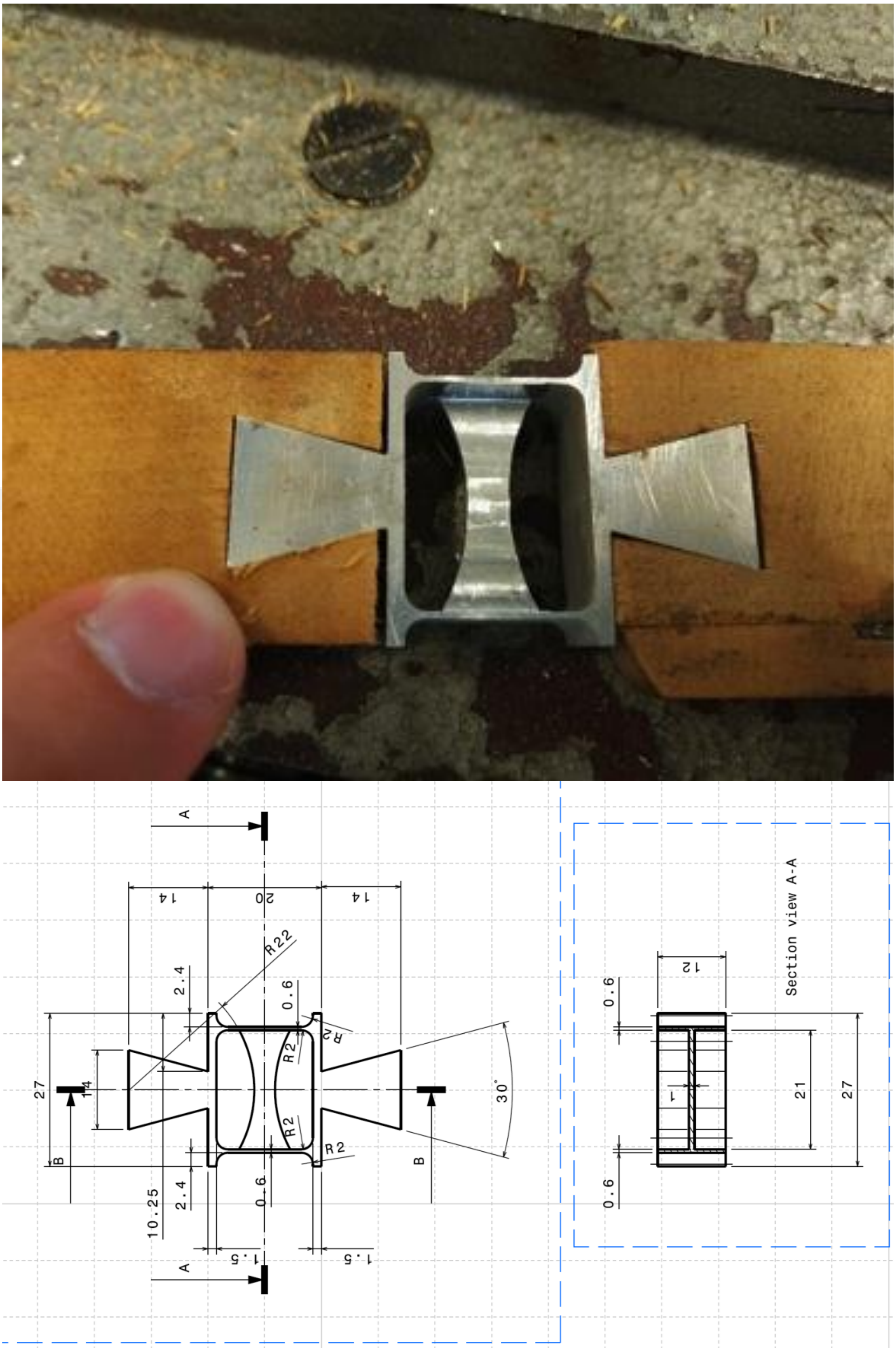



**Figure 3.20 :** Second prototype key – a design that could be produced.

The concept of FEA is that of dividing a problem into subproblems (finite elements) where an assumption over variation of a field variable (displacement, strain, etc. for elasticity problems) can be made and solving the main problem represented by complex differential equations and/or equation systems is converted into a linear or non-linear matrix manipulation and iteration algebra by combining each of the subproblems (the mesh generation and assembly process).

In this work, the geometry of a piano key, after parameterization, has been divided into elements in order to find the stress/strain distribution of the key under unit loads.

A strain that occurs at any point of an object that is under a force can be calculated by linear combination of strains occur as a result of each of the loads at that point with the principle of superposition. Since superposition is assumed to hold, our system is also assumed to behave like a linear system, which is in fact true. (Superposition is the principle in mechanics that claims that for a fixed point of a body, the total effect of a set of actions applied on a body is the sum of the effect of individual actions. In mathematical terms, equation 3.13 is said to hold.)

$$f\left(ax+by\right)=af\left(x\right)+bf\left(y\right) \tag{3.13}$$

A sensitivity matrix called **A** having number of columns equal to the number of strain-gauges and the number of rows equal to load conditions to be calculated is needed (called candidate matrix). Here, the candidate matrix is a set of strains per element of the FEA model. The maths of system calibration is a set of matrix equations 3.14, which is

$$\boldsymbol{\varepsilon}_{[nx1]}=\mathbf{A}_{[nxp]}\mathbf{f}_{[px1]} \tag{3.13}$$

where,

$\boldsymbol{\varepsilon}$: is a vector that contains strain values at n points

**f**: is a vector that force values effecting the object at p points

**A**: is the matrix that supplies the transformation between the force and the strain

The FEA model utilized is given in Figure 3.21. The finite elements model is built in HYPERMESH environment and the actual solver used is ABAQUS finite elements software. The material parameters in Table 3.3 are utilized for FEA analysis too.

The whole model of the piano key to be instrumented is in Figure 3.21. Although it is a model by finite elements analysis, the elements are absent at the render for the sake of better visualization of the key model.

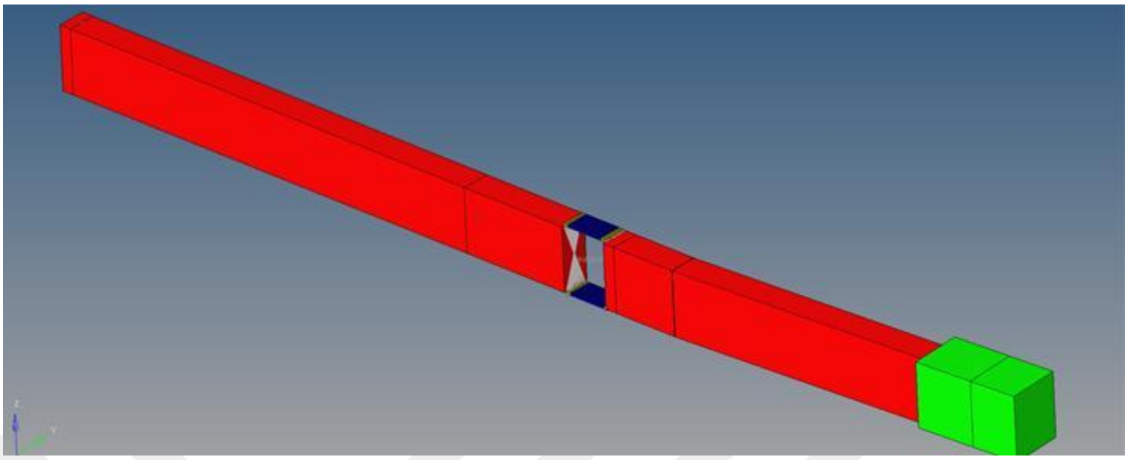


**Figure 3.21 :** The FEA model of piano key (elements 3d rendered).

Also in Figure 3.22, an illustration of the strains occuring at the Aluminum plates are colored in virtual domain.

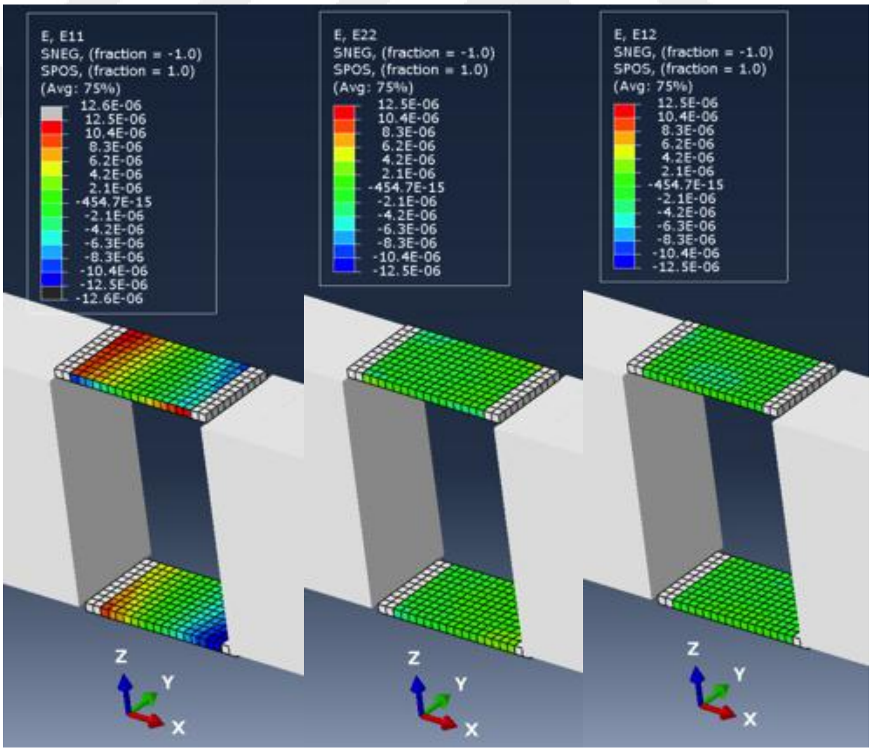



**Figure 3.22 :** Sample output of strain distributions in sensor region. notice the dominance of e11 (x-strain – on axis of the beam) over other strain components.

The design itself was altered many times to have a stiffer structure. These included embedded designs, introduced stiffeners and applying combined loading scenarios.

The views of strain distributions from these trails are provided in the following Figures 3.23 and 3.24. The strain response of the system did not change much.

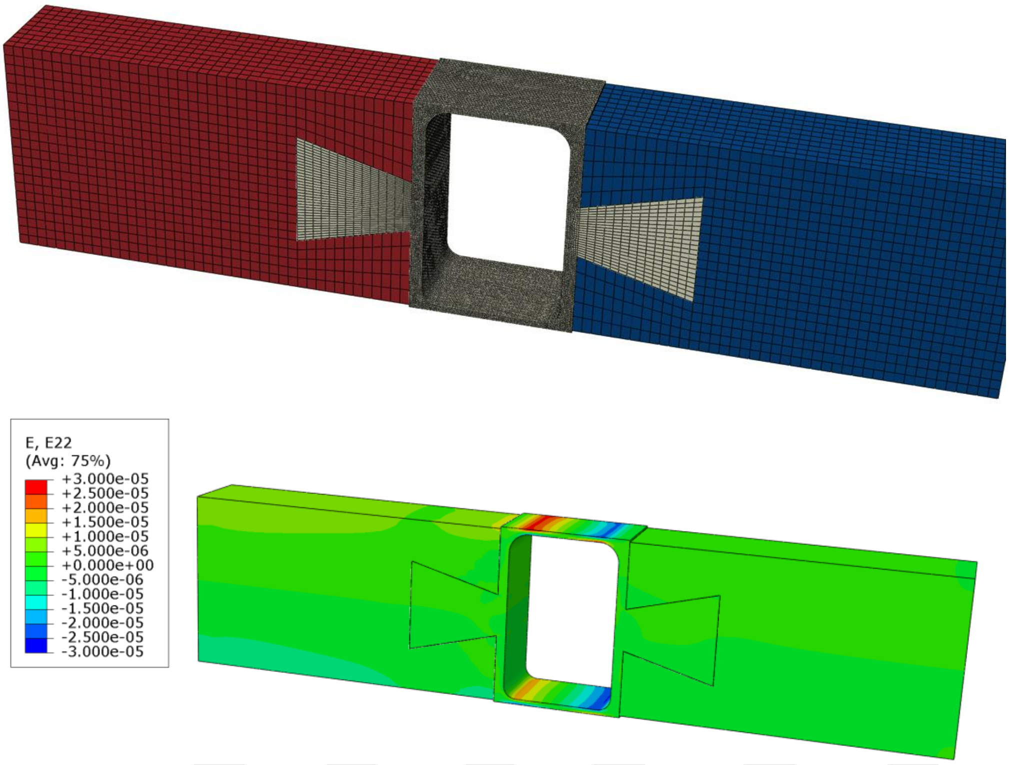



**Figure 3.23 :** Sample FEA mesh view of assembly and output of strain distributions in sensor region for axial strains of an embedded design.

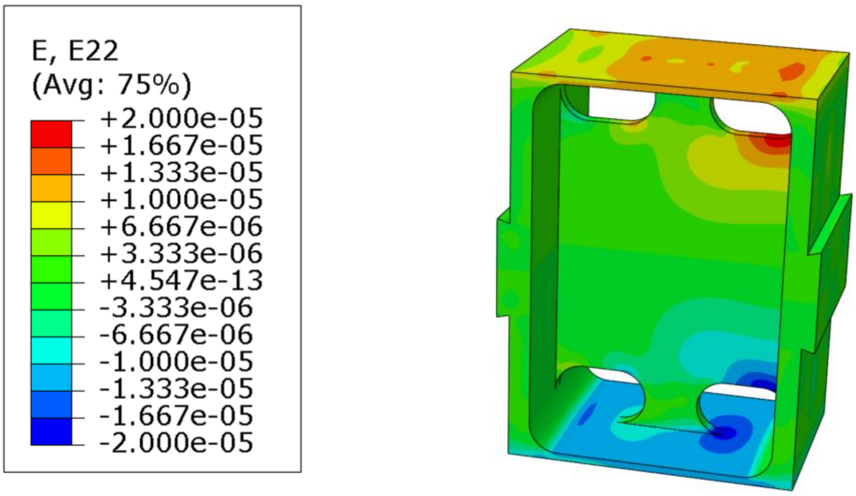



**Figure 3.24 :** Sample output of strain distributions in sensor region for axial strains of an embedded design with shear plate (wood & connections not shown).

After these trials, the final design was produced and installed, knowing that the strain distribution on the top and bottom sides was insensitive to the shearing plate at the center. Thus a prototype that was more suitable for production and sensitivity was designed. This final selection is shown in the following figure

The prototype sensor was thought to fix the aforementioned drawbacks. However, the design and its installation introduced more problems as progress developed. These can be summarised as follows:

- The woodwork needed found to have a base for installation errors. Appropriate tools for working the dovetail joint was hard to obtain and utilize. The behaviour of the wood to such an operation was not trustful. The misalignment during woodworking was intolerable when a set of side-by-side keys were considered.
- The sensitivity of strains to bending angle of the keys was not at a level that could be disregarded. The deviations due to the broken axis of the keys in the piano keyboard changed the measurements by the introduction of additional moments (torque) over measurement (sensor-part) cross-section, which disturbed the wiring and signal processing mathematics (i.e. changed A matrix for each key and each installation, which in turn is not feasible to maintain).
- The lack of separation of different inputs: The design couldn't distinguish between different load cases precisely, since the effects are all converted to local shear forces and bending moments at the cross-section of sensor installation. Thus, separation of signals due to touching location, the damper load, the behaviour of action and the touching of the key down to front rail punch was not possible. As a final outcome, to overcome these difficulties, it was decided to move to a better solution after evaluating its efficiency for 88 keys.

#### 3.4.6.3 Model 3 - The finalized design

The problems that have been observed with a single sensor at a specific location of the key yielded the consideration of distributed sensor locations. To identify the distributed locations, a re-visit of the load cases are required.

A summary of the load cases that are of interest to the scope of this thesis is summarized in the following table. The details of the assumptions that have been made to arrive at this conclusive list are given before in Section 3.4.4. It is also worth re-emphasise that, as aforementioned, the key system is non-linear in terms of the contact of the key to the front rail (see Figure 3.7) which changes the boundary conditions for the beam model of the key.

**Table 3.2 :** The list of load cases of concern for the instrumented key.

| | Definition | Remark |
|---|---|---|
| 1 | Punch Reaction | System Load when key is fully depressed |
| 2 | Mechanism Load | System Load(s) from Action (and Damper) |
| 3 | Vertical Finger Load F | Player Finger Load |
| 4 | Finger Moment My (Pos X) | Considering X Distance from Pressing Point to Punch Axis |

Within these three iterations, keyboard design is developed. In this prototype, it’s decided to install strain-gauge sensors directly on the wood. In order to install cables in tight environment, canals for cables are left in the keys. Thus, sensitive locations and modifications for measuring these quantities have been created on the key geometry. It has always been checked that the integrity, boundary conditions and operating conditions of the keys should not be altered due to instrumentation. Additionally, the electronic layout should not be visible to a player once it is fully installed.

The important positions that indicate a strain-gauge application can be summarized as follows:

- One location behind (towards the action side of the balance rail key pin) the balance rail and key button to measure the load arising from the damper and the action mechanism (which, in further studies can also be separated)
- Two locations to measure the finger force and its axial position on key towards the front rail side of the balance rail key pin
- Front of the key to measure the punch reaction and the situation whether the key is fully depressed or not

To increase local sensitivity, circular holes have been applied to selected locations according to application points of forces on the key structure and strength of wood. CAD model of this design is given in Figure 3.25.

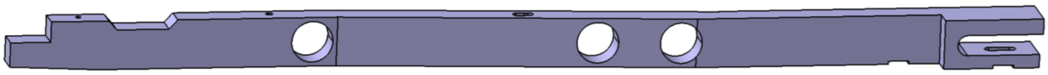


**Figure 3.25 :** Sensor locations (increased sensitivity regions) on the key geometry shown on cad model.

Moreover, each piano key has lead weights installed. This is to ensure that the key has a playable downweight and upweight to have. Extra holes for installing leads made and small weights installed in the cavity in the front of the key during installation (not pre-engineered) to be able to judge and minimize the lead use as in Figures 3.26.

**Figure 3.26 :** Holes for weight balancing leads.

Based on the localized instrumentation principle, 27 consecutive keys of the keyboard of a Yamaha C3 grand piano is modelled and manufactured. As seen in Figure 3.27, due to the production technology utilizing a computer numerical control (CNC) machine, the tolerances of the keyboard were achieved with no good fit with the original wooden materials. This required more trials with connection, scrap ratios, tolerance updates and handling of wooden material and machining procedures, which were not foreseen before the actual production had been completed, and caused an unexpected delay of completing the instrumentation.

**Figure 3.27 :** Iterations of key production.

### 3.4.7 Measurement of key travel

As the forces can be measured with the help of strain-gauges, there is also a need of measuring key position and travel continuously by displacement sensors for this stage. Besides overcoming the difficulties of installing strain-gauge sensors, selecting appropriate displacement sensors was a demanding task. There is limited area for installation, not sufficient distance for the focus of these kinds of sensors, their cost can exceed our project. Optical displacement sensors, in Figure 3.28, from brands like Omron, MicroEpsilon, E3Tam, Singer-Instruments, Lase, Omega, Solarton etc. are found insufficient due to the constraints like tight space, field of view (FOV) and budget.

**Figure 3.28 :** Stripe and point laser sensors with FOV problems

Also, there are plug-n-play optic displacement systems like (QRS PNOscan, PianoDISC Prorecord, Pianoforce Keescan) produced with the aim of, getting MIDI data from acoustic pianos. After long correspondence with them, it is understood that these products do not satisfies necessities technologically for such scientific research. It is decided to use potentiometric displacement sensors instead of optical sensors. LMT 14 5k Linear Potentiometric Sensorsproduced by Opkon, seen in Figure 3.29 (specifications in Figure A.2), are found to be efficient for this project.

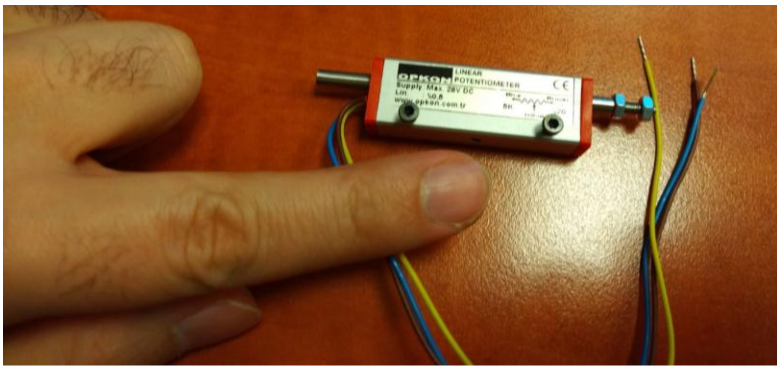


**Figure 3.29 :** Linear potensiometric displacement sensor.

Due to tight spacing requirements, a special sensor layout has been designed for consecutive installation of sensors, to make one displacement sensor for each key fit thru the keyboard, which are installed on an aluminum base, that fits onto key stop rail screws on the keyboard layout. The design is based on the localization of the keys, their angular deviation of axes and sequence. The CAD view and a view during installation are given in Figure 3.30 (diagram in Figure A.3).

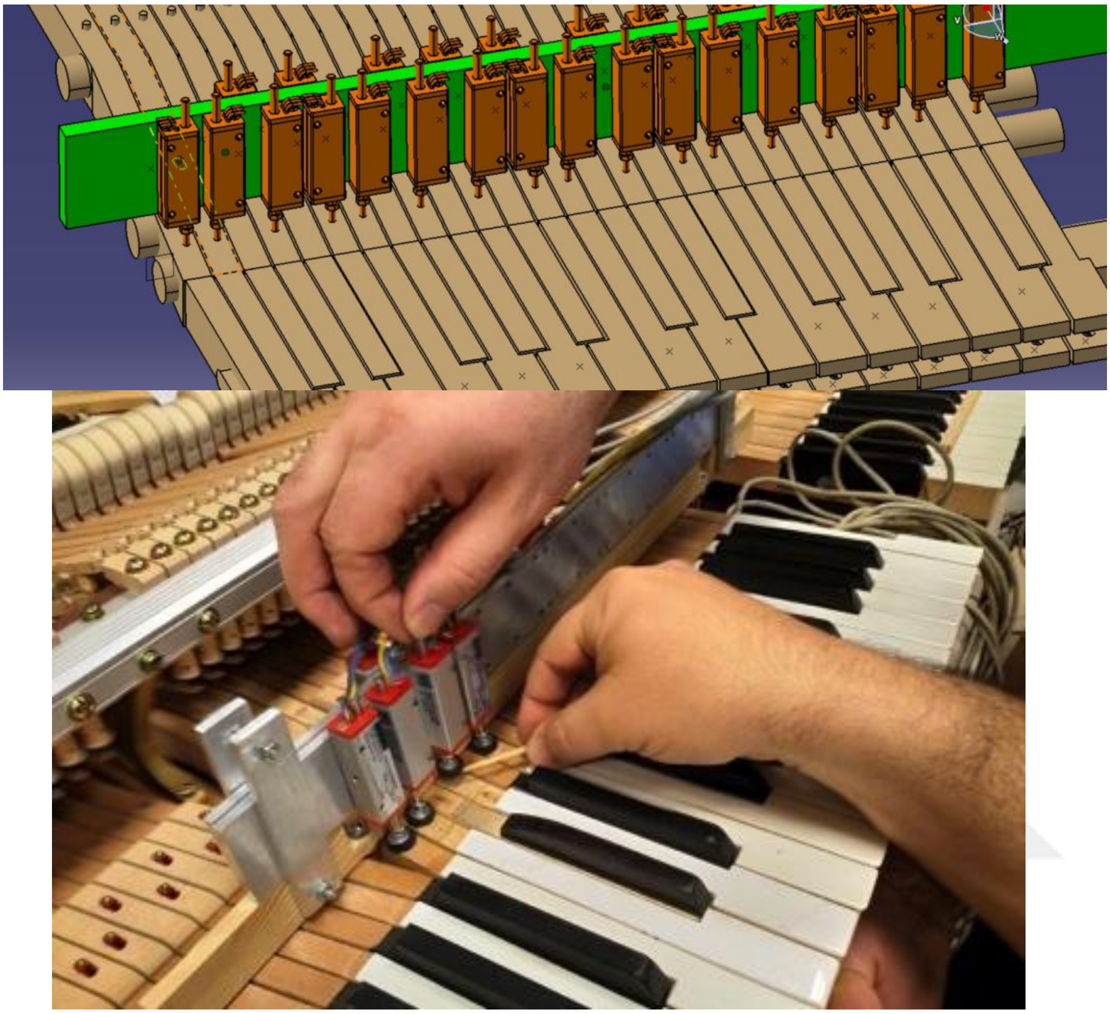


**Figure 3.30 :** Installation of displacement sensors.

### 3.4.8 Additional equipment for tests

The main purpose of this thesis is to manifest the properties of more effective touch to the piano keys that lead not only well playing but also virtuosity and the core challenge of this path is quantifying the touch. In order to achieve this, besides obtaining piano keys to install sensors for measuring the touch, various special equipment is also needed. Sensors, super flexible thin cables, appropriate key tops for black keys and key front covers for white keys of Yamaha C3 grand are supplied after market research.

The piano key has a small element attached to itself called capstan, which is a specially produced screw that transfers the motion of the key to the whippen and the hammer. The top of it should be smooth and egg-shaped. Its head should contain two holes going to the opposite side in order to put a spindle to turn it for the sake of regulation. It is also tried to be manufactured (in Figure 3.31 right) but technical difficulties couldn't be overcome and it's decided to be better purchased. Other auxiliary parts such as the backcheck, which is a leather-covered triangular wood attached on a bent rod at the end of each key and whose function is to catch the hammer and block its rebound after the key played and the lead weights in the front part of the piano key in order to balance the weight of the wippen and hammers are supplied externally. Backchecks, capstans and leads that seen in Figure 3.31 (left) maintained from Germany, Jahn Pianoteile.

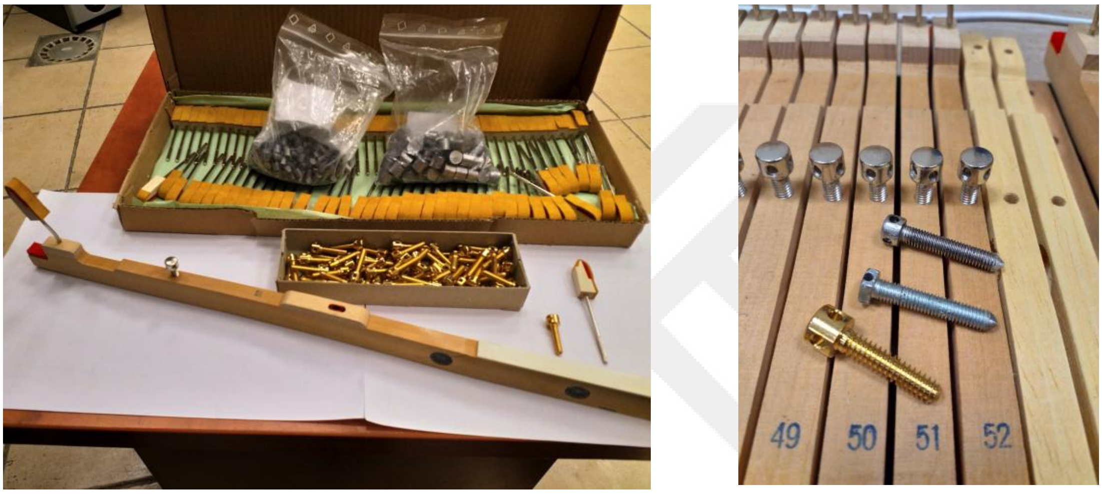



**Figure 3.31 :** Auxilliary equipment.

### 3.4.9 Cabling

There are four strain-gauge sensors in each key. Each sensor needs three cables so each key has twelve cables attached to it. Cables must be as flexible as they can be otherwise they obstruct the movement of the key and the experiments conducted with such a system can not be trustful. They must be also be shielded to minimize electromagnetic disturbances. Within the scope of this thesis, after market research, shielded ultra flexible Bürklin miniature control cable, (specifications in Figure A.4) is purchased (Figure 3.32).

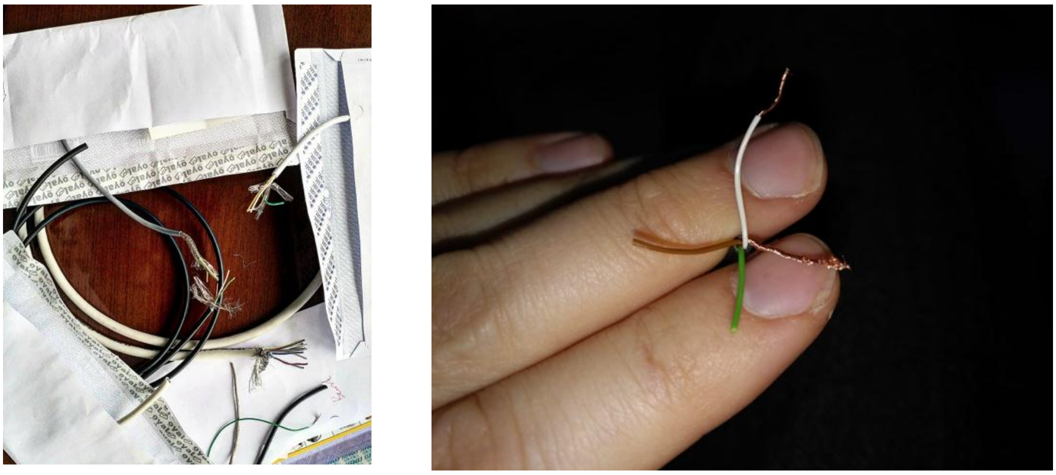


**Figure 3.32 :** Cable variants investigated.

### 3.4.10 Data acquisition

Strain data from different positions have been collected synchronized for different loading conditions by a multi-channel data acquisition system, manufactured by British company Prosig, Inc, UK seen in Figure 3.33. For tests, 2000 Hz sampling frequency has been selected. It has been observed during trial studies that, lower sampling rates than 2kHz has yielded in loss of data especially in sharp gradient actions such as *staccato* playing.

**Figure 3.33 :** Data acquisition system.

## 4. RESULTS OBTAINED BY PROCESSING RECORDED DATA

Tests done with two keys C3 (key no 28), D3 (key no 30) which are the third prototype and also have displacement sensors on. Figure 4.1 shows the codes for strain-gauges.

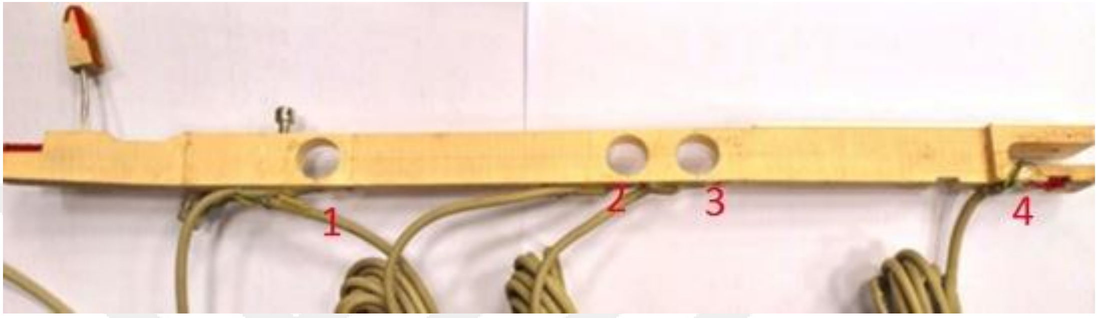



**Figure 4.1 :** Strain-gauge codes.

In the following figures, i.e. the displacement-strain charts derived from recorded signals on prototype keys, it can be clearly distinguished that during playing, the overall behaviour is dominated by the inertial effects of the system when the key is hit for a *forte* sound. However, for *piano* playing, the sense of the action mechanism internal friction effects and constant-force-travel of the mechanism (i.e. constant load measured from mechanism (gage #1) for some range of displacement after there is a release) is "feel-able".

In Figure 4.2, the displacement of the key with respect to time can be observed while playing *forte staccato*. The key starts moving instantly at the time of 43.912. The speed of the key starts to decrease when the displacement value is around -1 at the time of 43.925. The key continues to slow down until the displacement value reaches -1.3, then accelerates again and continues to move down until the time of 43.95. It seems that this slowdown and then speeding up again and continuing in the same direction is the moment when the jack touches the knuckle and let-off happens. There is a small delay at the time of 43.975. Key return speed decreases again for a short time. This is the effect of the hammer falling on the mechanism.

It can be seen that after the key returns to its starting position around the time of 44.01, it continues to fluctuate gradually decreasing for a while. It is a natural oscillation that takes place due to the structure of this system and continues until its energy is exhausted. The fact that the key never stays in a fixed position so that the displacement values change constantly is a sign of *staccato* playing. In *staccato* playing, the key is pressed for a short time, that is, the force is applied for a short time. The relatively quick change of displacement (compared to Figure 4.8 for example) indicates that the playing dynamic is *forte*. Also at the beginning of the movement of the key, the reverse movement of the displacement indicates that the finger waits on the surface of the key and makes a small preparatory movement before playing.

In Figure 4.3, strain changes in the key according to time can be observed during *forte staccato* playing. A value of -175 for the strain indicates that it is a press called *forte* (on the other hand, in figure 4.8, the maximum strain is around -55 which shows that is a piano playing). It is seen that the strain increases up to the time of 43.925.

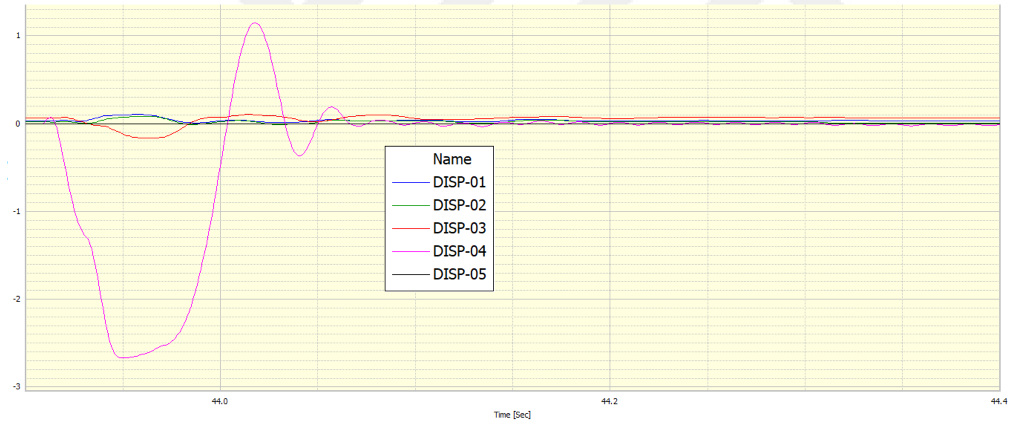



**Figure 4.2 :** Displacement versus time graph for *staccato forte* playing.

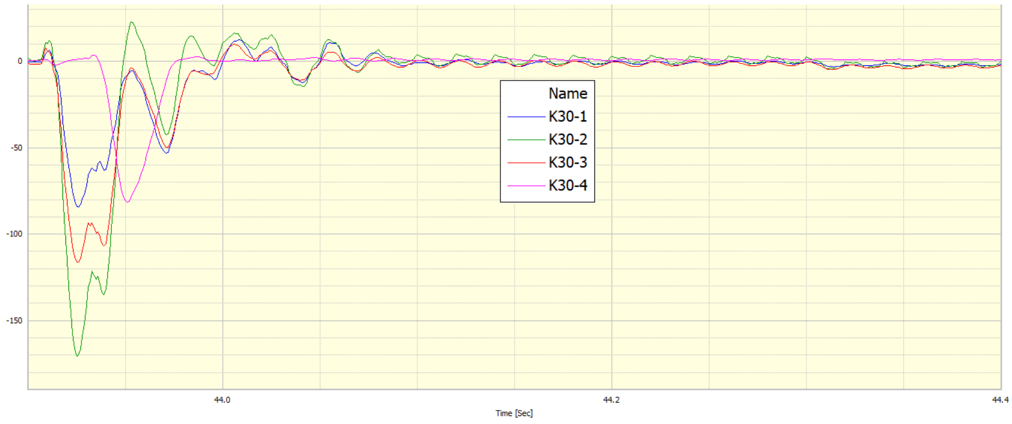



**Figure 4.3 :** Strain versus time graph for *staccato forte* playing.

K30-4 starts to produce values around the time of 43.937. This indicates that the bottom of the key has not touched the front rail bushing until this moment. The fact that it gives the highest absolute value at the time of 43.95 confirms that the moment the key hits the bottom is at the time of 43.95 and the displacement in Figure 4.2 (the highest value is -2.7) is obtained at the time of 43.95. It was seen in Figure 4.2, that the key returned to its initial position around the time of 44.01. It can be seen in Figure 4.3 that the button and the mechanism make reactions and thus transients before and after this moment, which will create gradually decreasing strain fluctuations.

In Figure 4.4, the position of the key and the strain change in the key can be seen during *staccato forte* playing. The instant of the keypress is located on the right at the point when the displacement is 0. As the visible end of the key goes down, the displacement gains a negative value, while the strain values also increase (in the negative domain). When the front of the key reaches the bottom and starts to return, the curves turn to the right again. The increase in strain until the displacement value reaches -1 can be seen as the values increase and reach up to -175 and enlargement of the gap between K30-2 and K30-3. The reason the strain seems to decrease when the tip of the key reaches the bottom is because the system is in a state that various dynamics of mechanism (like transients, occilations etc.) occur. Likewise, when the key starts to return, the displacement value is around -2.5 mm, the strain-gauges K30-1,2,3 make new local peaks.

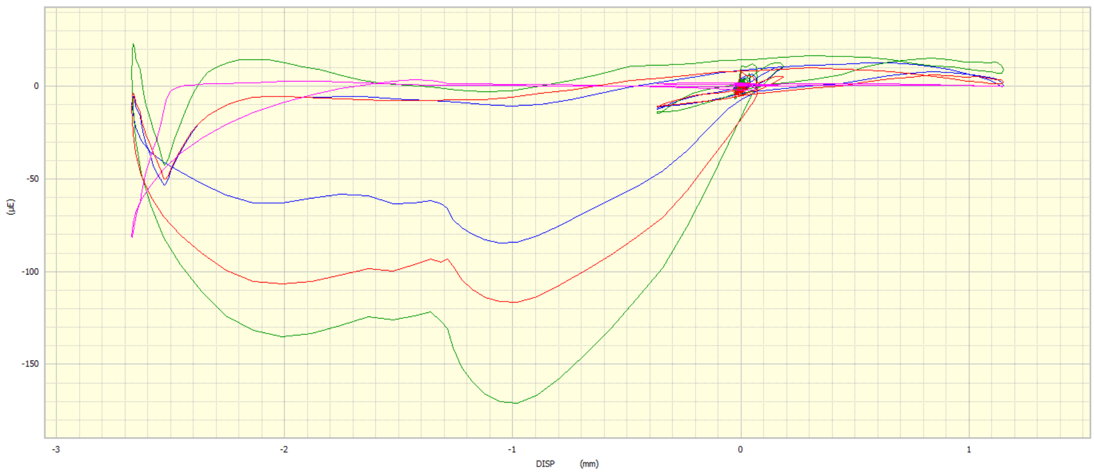



**Figure 4.4 :** Strain versus displacement graph for *staccato forte* playing.

When the key continues its free movement and returns to its starting position, there is a lot of immediate reaction and the sensors generate a lot of data, so a knot-like formation is seen at the 0 point of the displacement. The small fluctuations of the key after it is released can be seen when the curves go to the right again on the graph, and when many new values are formed in the horizontal plane.

In Figure 4,5, the displacement of the key with respect to time while playing *forte* but now in *legato* touch can be observed. The key to which the Displacement-04 sensor is connected was pushed to the very bottom, that is to the value of -2.7, then left back to the -2.5 position and held there from the time of 30.68 to 31.4. The increase in the values of Disp-04 while the values of Disp-02 decrease shows that the playing of these two keys has a *legato* interrelation. Because the playing in Figure 4.2 was *staccato*, neither overlap with other sensor data nor a constant displacement value could be seen over any period of time. Although there is a *legato* relationship with the key pressed before, no other key was pressed afterwards.

The high slope of the displacement curve is an indication that the key is pushed fast, that is, pressing speed is high so the playing is *forte*.

The key is suddenly released even though it was held at the bottom of the key for a relatively long time. This is understood by the steepness of the curve at the time of release and the opposite value in displacement after release. The abruptly released key fluctuates on its own.

In Figure 4.6, strain changes in the key according to time can be observed during *forte legato* playing. Disp-4 produces values between in the times of 30.58 and 30.65. This explains the key release from -2.7 point to -2.5 point in figure 4.5. When the key reaches the -2.5 displacement value, the contact with the cushion under the key ends. So the values of K30-4 converge to 0.

Continuing to apply force after the key touch the keybed does not have a positive effect on the playing, it puts extra strain on the muscles and joints, and makes the pianist tired. It is an attitude that can usually be seen in beginners. Monitoring the magnitude and timing of these strain values during finger technique studies shows whether the exercise is performed correctly. On the other hand, those who use the arm weight technique are much more likely to continue to exert force at the bottom of the key. Eventually, the related muscles of the arm are intentionally relaxed and its weight is dropped on the key and thus on the bottom of the key. In other words, by following these values, it can be understood who uses the heavy hand technique (arm weight technique) or the quiet hand technique (finger technique).

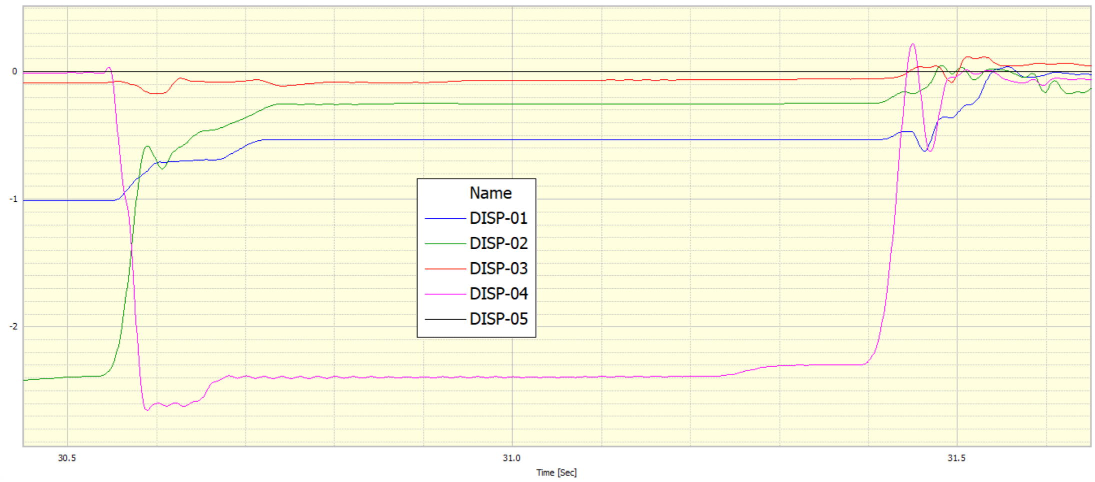



**Figure 4.5 :** Displacement versus time graph for *legato forte* playing.

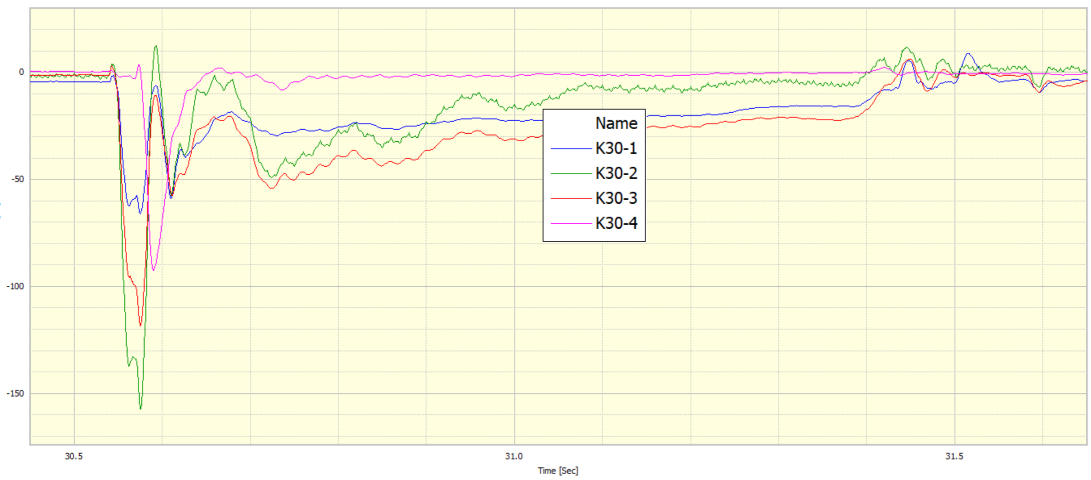



**Figure 4.6 :** Displacement versus strain graph for *legato forte* playing.

In Figure 4.7, changes of strain related to position of the key can be seen during *legato forte* playing. Although let-off (starting of the free flight of the hammer) is observed around the value of -0.9 in the displacement axis, the strain continues to increase until the displacement position of -1.8. This is an indication that the force applied to the key continues to be applied to the further stages of the key's movement if it is compared to the *staccato* touch in Figure 4.4 where the extremum strain value is at the displacement position of -1.

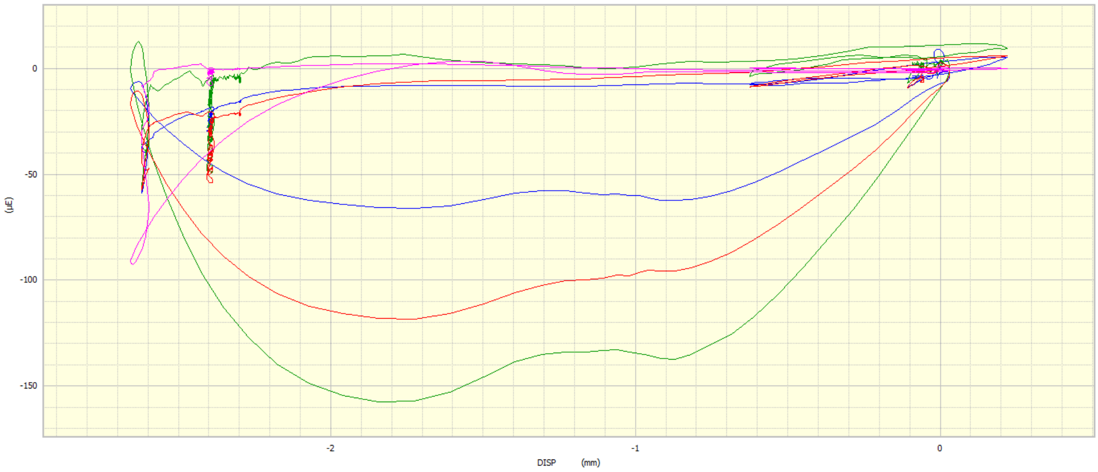



**Figure 4.7 :** Strain versus displacement graph for *legato forte* playing.

As the key goes down towards the value of -2.7, the strains values seem to approach 0 because the system is not stabilized yet due to transients that fade quickly. Therefore, many strain values can be seen on the graph, forming a vertical line at -2.7 and -2.5 values of the displacement where the key is pulled back and held a little. These accumulations were not seen in Figure 4.4 because the keypress was *staccato*. During the movement of the key in *staccato* playing, contact was applied for a short time and the system was left to itself, whereas the contact continues in *legato* playing.

The difference between *legato* and *staccato* passages played at the same speed is that each key is pressed for a shorter time in *staccato*, that is, each sound is heard shorter (in situations where the sustain pedal is not utilized). This means that each key will be forced for a shorter period of time. Although articulated (non overlapped) playing is more prominent in the playing traditions of the Baroque and Classical Era, it is one of the fundamental techniques of piano playing valid for any period of music.

In Figure 4.8, the displacement of the key with respect to time while playing *legato* but now piano can be observed. It seems that the playing is not *staccato* since a fixed value is seen on the horizontal axis. The slower decrease of the displacement values compared to Figure 4.2 indicates that the keypress is slower so the playing is *piano*. Disp-02's gaining value before Disp-04 reaches 0 shows that there is a *legato* relationship between two key presses.

The duration of these overlaps may vary depending on which interval there will be a *legato* relationship, in which register they are played, which period a piece is played, acoustics and ultimately at the interpretation of the performer. For example, while consonant intervals like perfect 4ths and 5ths can be played more *legato* in the Baroque and Classical repertoire compared to other intervals. On the other hand, in modern and contemporary era works, *legato* will not be heard inappropriate even in minor 2nd intervals, which is a dissonant one.

In Figure 4.9, strain changes in the key according to time can be observed during *piano legato* playing. Strain reaching an extremum of -47.5 value shows a much softer playing compared to Figure 4.3 and Figure 4.6. The fact that K30-4 does not take any value confirms that the key does not move enough to touch the felt under the key. It is also consistent with the displacement value approaches at most -2, not -2.7 in Figure 4.8.

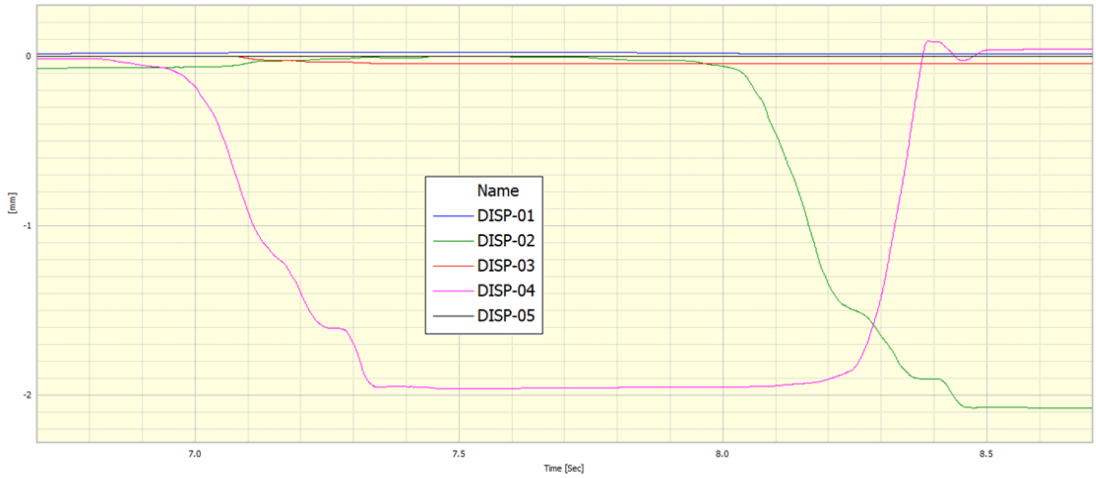



**Figure 4.8 :** Displacement versus time graph for *legato piano* playing.

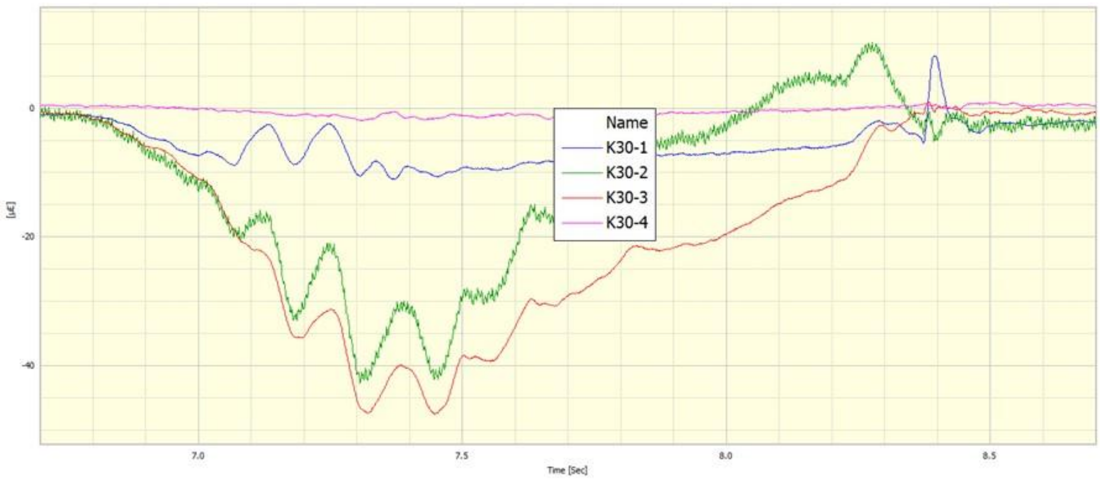



**Figure 4.9 :** Strain versus time graph for *legato piano* playing.

K30-1 moves more independently than k30-2 and k30-3 compared to previous charts. It can be said that playing the piano, that is, moving the key slowly, puts less load on the key on the capstan side. The reason for this is that the mechanism does not resist the motion as much as the *forte* examples. If there is less action (the *piano* touch) then there is less reaction.

Sudden increase and decreases of strains and transients due to free flight of the hammer at at the time of 7.08 and then falling back onto the mechanism at the time of 7.19 can be clearly seen. In Figure 4.8, it can be understood that the reason for the constant displacement value seen around the time of 7.25 is the return of the hammer on the mechanism around the time of 7.19. Since the force applied by the finger is higher in *forte* playing, these transients were relatively smaller, but since the maximum strain scale of the graph is less in piano playing (up to -170 in *fortes*, -50 in *pianos*), the transients were reflected on the graph as if they were larger.

In Figure 4.10, the position and the strain change in the key can be seen during *legato piano* playing. In order to be able to play soft, the flight of the hammer should be slower.  And to provide such a subtle control, pianists want the let-off to be set as close to the bottom of the key as possible. Due to the experimental conditions, such an adjustment was not possible, and the result can be seen here. The let-off (free flight of the hammer) took place here at around -1.2 displacement value, not close to -2.7.

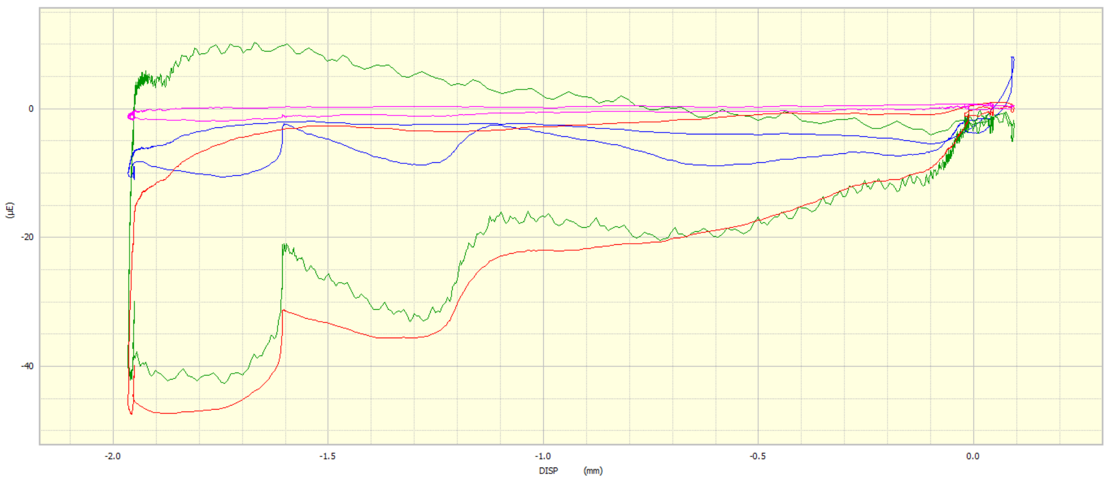



**Figure 4.10 :** Strain versus displacement graph for *legato piano* playing.

The sudden increase in strain when the key is in the -1.6 position may indicate that the hammer hit the strings and returned to the mechanism. In fact, this also coincides with the constant 1.6 value seen between 7.25 moments and 7.3 moments in figure 4.8.

In Figure 4.11 *legato* playing is shown. Overlaps of "press" on keys can be seen (from displacement sensor data, as well as timing between gage readings K28-2 and K30-2). Keys B and E are not instrumented yet (they are gaps in signals). The final note C is pressed down hardly to "feel" that it is the last note by the pianist (punch reaction is standing there). The bounce on K28 is higher than K30, a possible problem with key regulation.

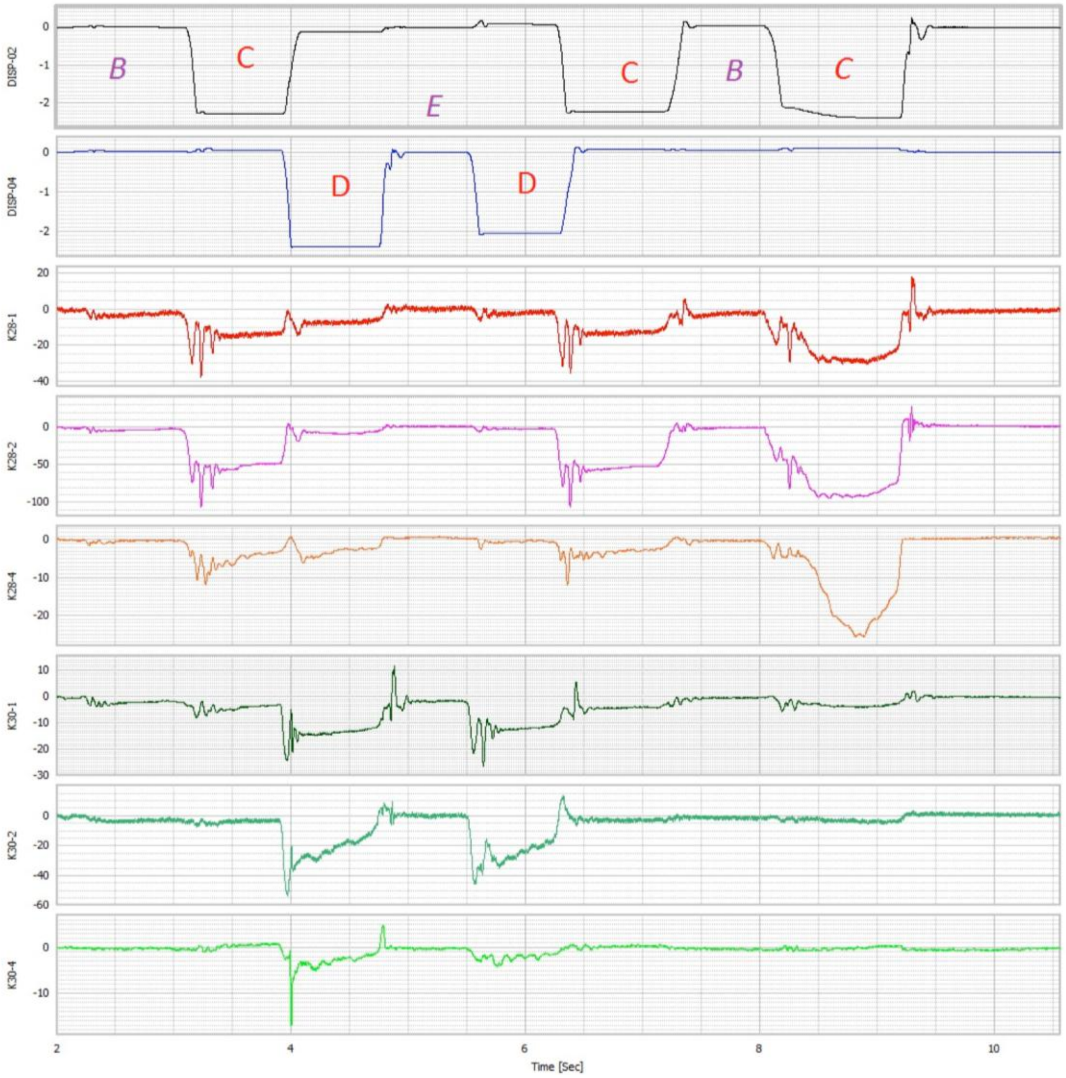



**Figure 4.11 :** Displacement and strain versus time graph for *legato* playing.

It can also be seen that during the key is pressed down, the pressing force gets less by time as the melody progresses (to other keys).

The punch reaction sensor also distinguishes clearly whether the key is fully depressed (or even slightly touching the base) during playing or not. One can train himself to fully use the stroke but not touch the end by such an aiding technique.

In figure 4.12 waveforms are obtained while playing the sequence B-C-D-C-B in *legato-piano*, *legato-forte* and *staccato-forte* styles (from left-to-right). The requirement for high sample rates (min 2kHz) is clearly seen. Forte always hits the ground here. The loading pattern looks almost the same for *legato* and *staccato* "touch" (i.e. the generation of sound), however, is not. (see the first three figures, the reactions are different up to some point on the keystroke).

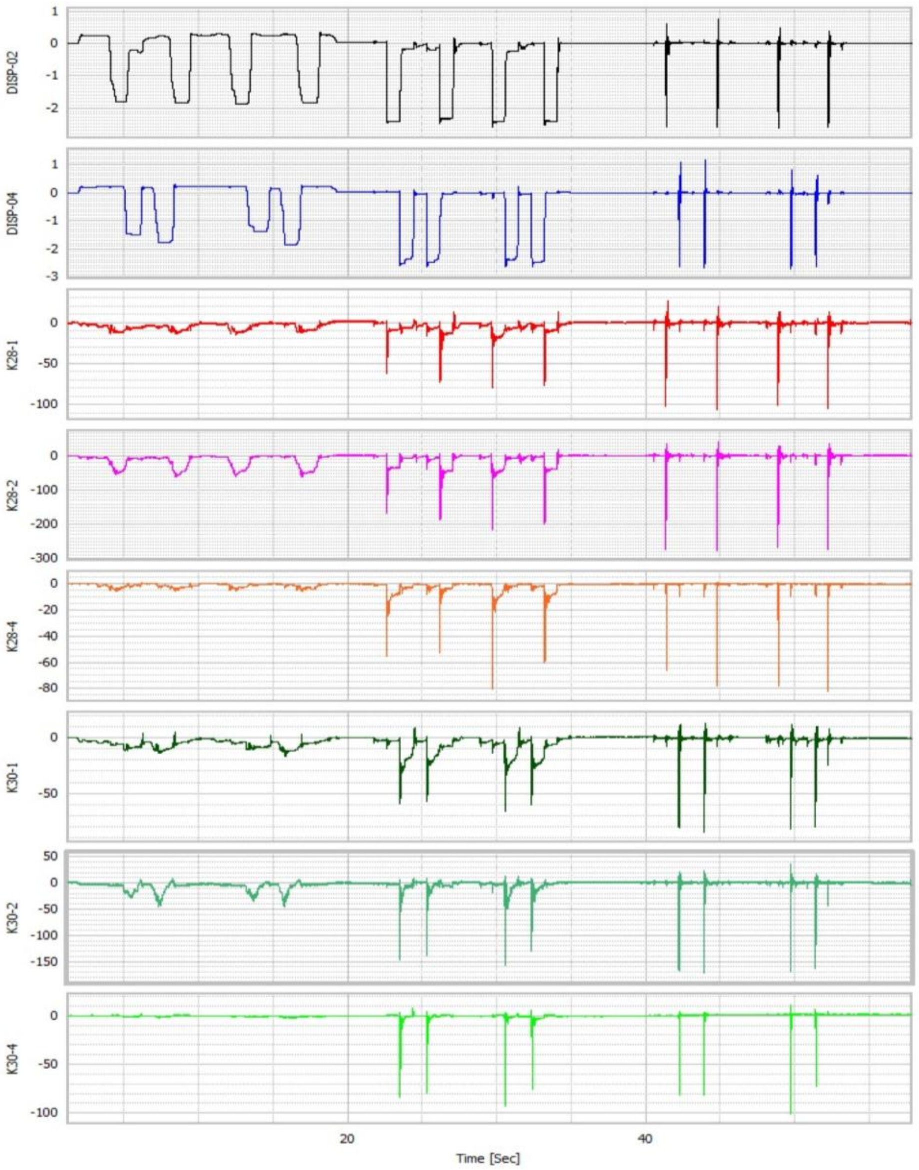



**Figure 4.12 :** Displacement and strain versus time graph for *legato piano*, *legato forte*, *staccato forte* playing.

In Figure 4.13, one can see how playing technique changes can be identified via force measurement at critical points: K30-4 shows playing with punch touching down (t=16.5s) and not touching the base (t=18.0s). This may explain the modifications of technique during playing in order to ensure efficiency. This kinds of technical differences activate different set of muscles. Although it is acted unconsciously, changing working muscles frequently may be an indicator of efficient playing and expertise.

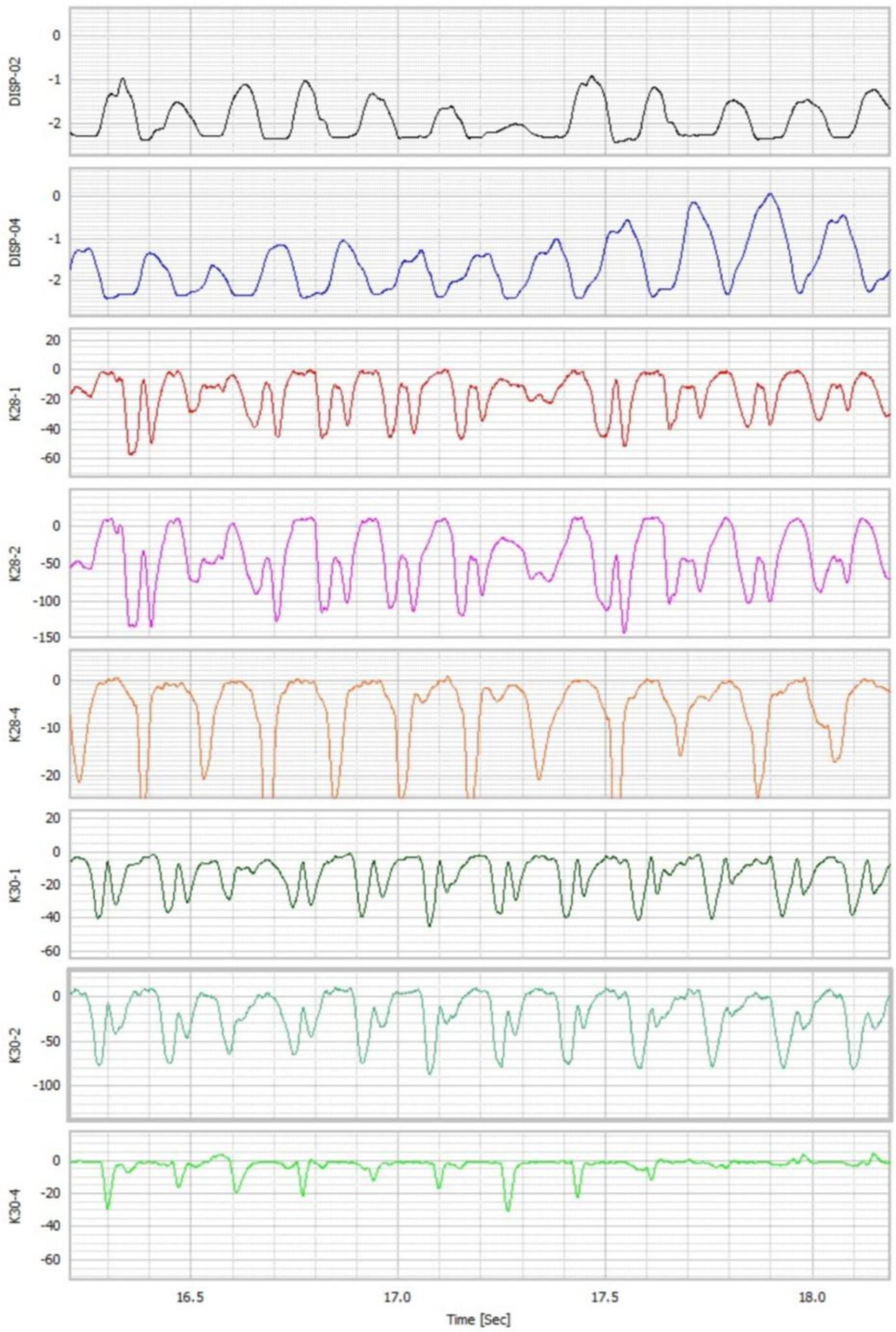



**Figure 4.13 :** Displacement and strain versus time graph for alternating techniques.

In Figure 4.14 the higher the speed, the more profound the double-frequency feeling of the mechanism load at the fingers get, along with completely changing patterns of key travels during a trill (a musical ornament consisting of a rapid alternation between two adjacent notes) C-D can be seen.

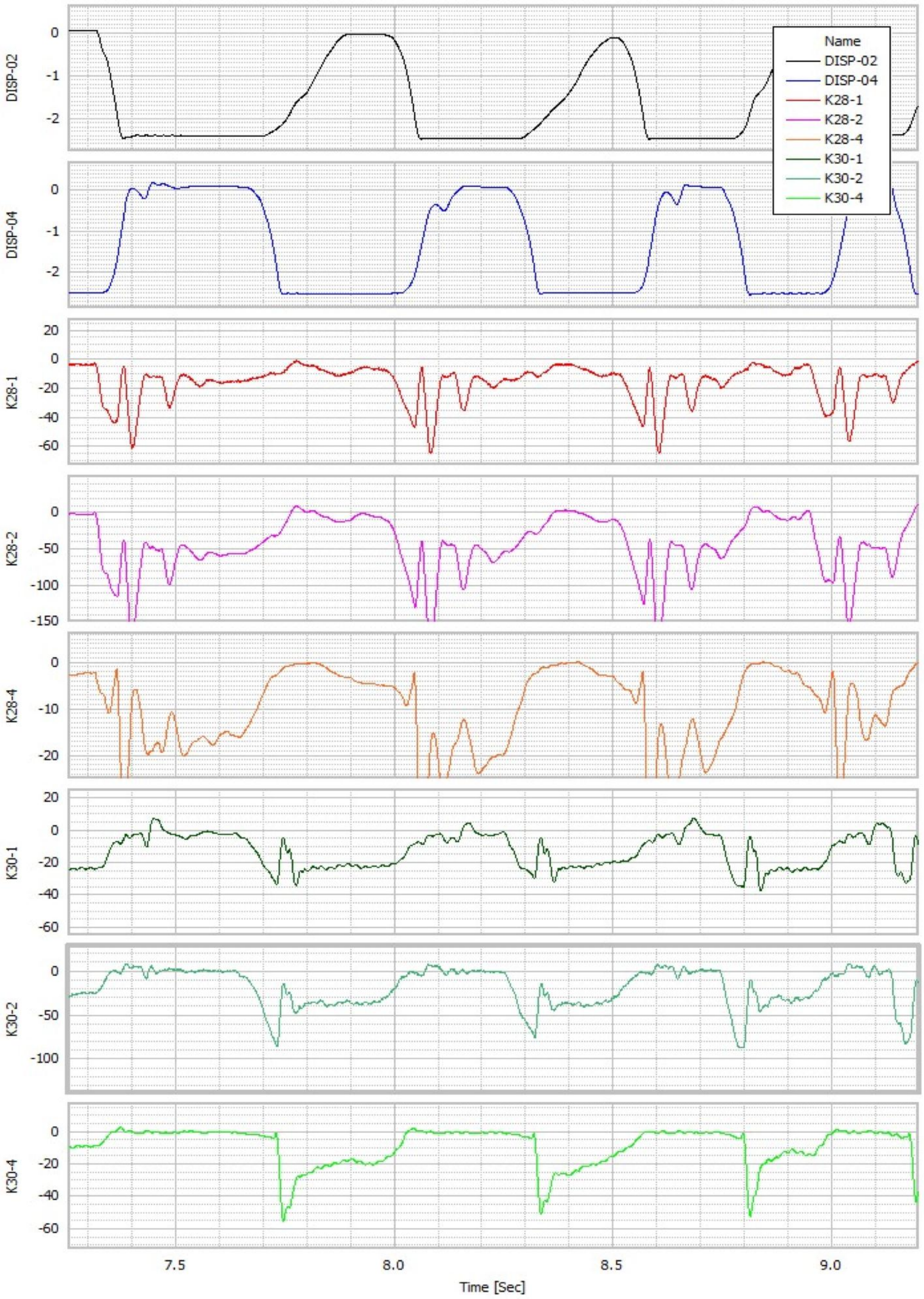



**Figure 4.14 :** Displacement and strain versus time graph for accelerating trill.

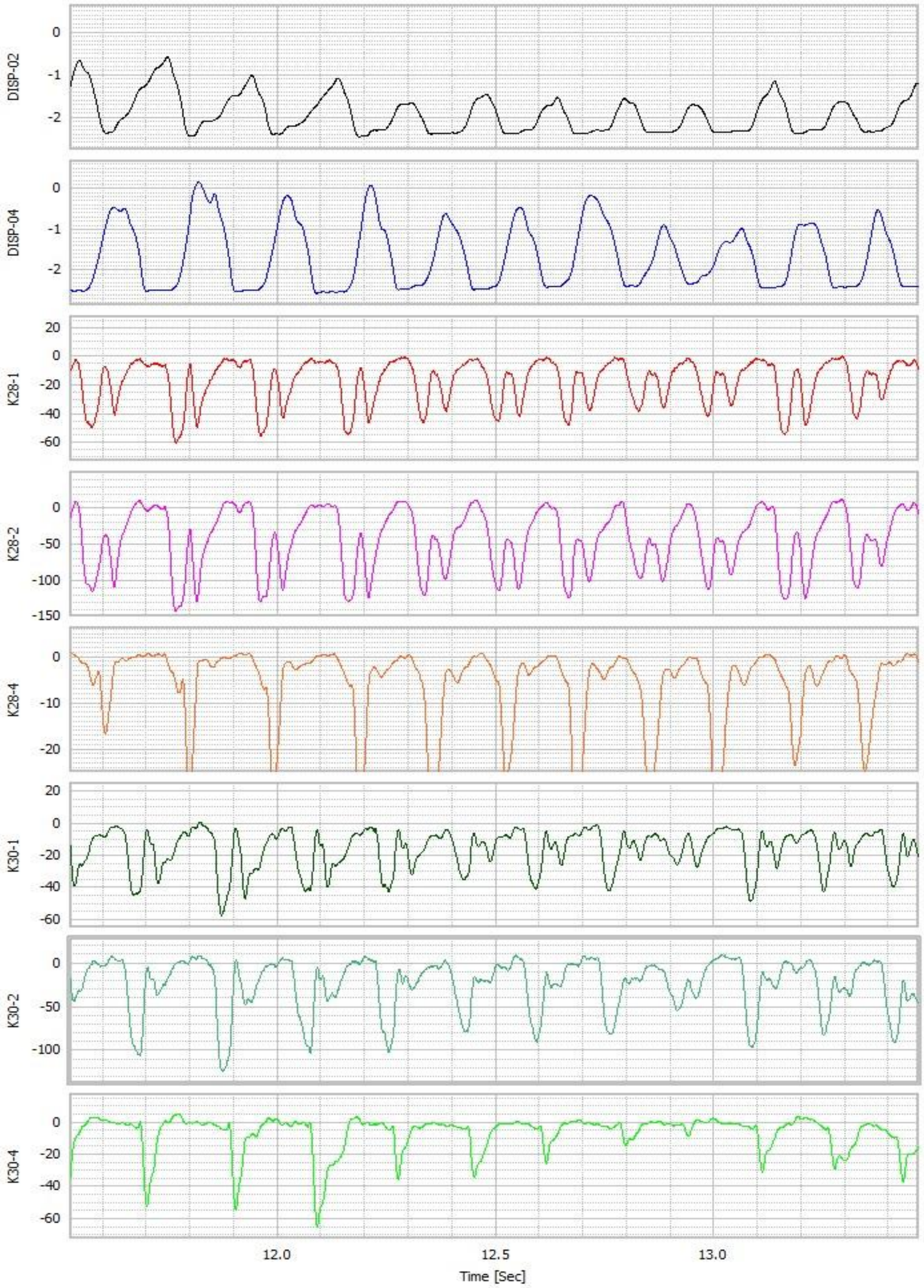



**Figure 4.14 (continued) :** Displacement and strain versus time graph for accelerating trill.

The different pressing release characteristics of the keys are easily shown at a slow tempo. At the beginning they may be interpreted as slow lifting thumb as the slope of the k28's curve is not vertical as k30 at the release part but if the fast section is inspected, the conservation of the same slope can be seen.

In Figure 4.15 a missed note can be detected around the times of 17.3-17.4.

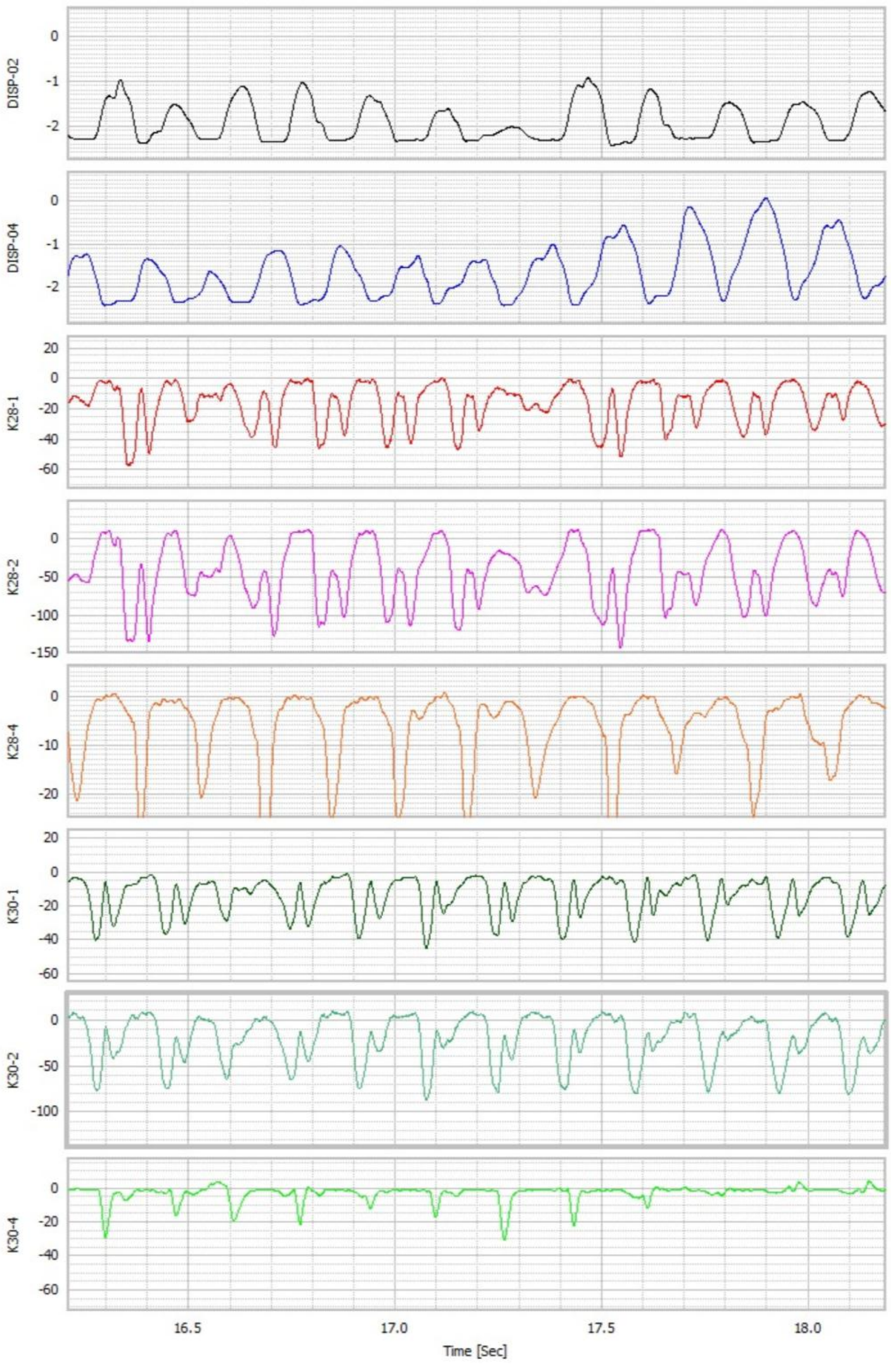



**Figure 4.15 :** Missed note.

## 5. CONCLUSION

The piano is one of the most demanded musical instruments. Despite its high manufacturing cost and price, it is the number one instrument to begin music lessons with. Piano’s popularity may come from its functionality across almost all genres of music due to its orchestral interpretative capabilities. The acceptance of piano and its technical evolution has been continuing since its invention but piano pedagogy couldn’t change parallel to piano's evolution. Although there is research based on today’s quantitative methods, this approach couldn’t be appreciated in piano education. On the other hand, the underlying facts of the piano virtuosity are unknown but technologies that can collect and analyze data derived from the virtuosos has the potential for solving this mystery.

This study presented a new application of engineering technology to investigate piano playing techniques. The results of this innovative application indicated that the force transducer piano key is an important progress for objective investigation of piano playing techniques. The data gathered by this system, even at the prototype level, could provide objective information on piano playing in a very different way in comparison to MoCap, EMG, depth-sensing etc… The main characteristics of playing such as *staccato, legato, forte* and *piano* are differentiated in the plots of acquired data containing time-histories of force and displacement values of keys. The data is also seen to provide detailed information on the behaviour of the piano action throughout different stages of the key pressing across different playing techniques. This way, without affecting the piano playing process of the player, the forces applied to the keys could be measured.

To advance the work, precise calibration of each instrumented key can be handled a priori recording data for meticulous evaluation of finger force and mechanism reaction values. This is a complicated task of applying known loads to known locations and measuring the output of the sensors which yields mostly linear relations of loads and strains based on the installation and geometry. Then, the calibration should be checked at regular intervals to be sure that the deviations are within reasonable tolerances. Anyway, even without the calibration, the system was able to collect reliable data allowing the comparison of different playing techniques.

In the sample data examined within the scope of this work, the dampers have not been included to keep the system a little more simple. If exists, the dampers will influence the loads on strain location “1”, which may need additional instrumentation and/or some more aggressive data processing to distinguish between the responses with the dampers active (sustain pedal not pressed) state and dampers inactive state. However, since the technique is functional, the installation and integration of additional sensors to the system are quite straightforward.

This study was carried out without any financial support. With the help of investment, the work can be enhanced with the use of additional sensors. Awareness of the hammer’s behaviour is seen to be providing beneficial data for investigating playing dynamics. Although the timing of let-off and the moment the hammer drops back on the mechanism can be interpreted through the already obtained data, it will be useful to have information about the displacement data (travel dynamics) of the hammer to be certain of the reasons for some of the value changes observed in the graphs. Also, in addition to displacement data of the hammer, adding sound recording to the system may provide a great advantage in evaluating the data. Making comparisons over -at least- sound pressure levels instead of non-quantitative terms such as *forte* or *piano*, which are used as the terms of loudness in music, would be an important step towards obtaining more reliable findings.

Besides adding hammer and displacement sensors and sound recording, all keys of the piano can be converted into force transducers. In this way, a much broader analysis of piano playing can be done. Having such a broader compass, the forces exerted by different pianists on many musical structures like a whole piece or a passage of it or various scales, arpeggios, octave passages, tremolos, parallel triads, etc. can be examined. By integrating motion capture or depth-sensing image processing technologies that can track the finger, hand, wrist, elbow, shoulder, body and foot positions of the pianist into this system and convert them into quantitative data, a great move towards objective examination of the postures, the movements and the forces which is called as the piano technique can be done. However, laborious data science support is expected to be utilized to analyze the immense amount of data that will originate from the installed numerous sensors. But, even if the analysis may not be done fully at first, collecting data of this quality and quantity from virtuoso pianists is sure to allow the immortalization of their artifice, and their ways of playing the piano will always be open to examination for distant future.

In addition, the piano keys converted to force transducers have the potential to shed light not only on the study of pianists but also on the efficiency of the piano's mechanics. For this, force transducer piano keys will need to be installed on different pianos, various predetermined forces will then be applied to the keys by an automated force actuator and the responses of different mechanisms to the same input forces will be able to be measured. In this way, the advantages of different piano action designs and also different adjustments on the same piano action can be quantitatively revealed. Also, it can be understood whether or not the mechanisms of a particular piano work consistently for each key.

Quantitative investigation of piano technique has the potential of redefining piano pedagogy. Via this knowledge, more pianists can achieve the level of music performance desired by themselves and by the composers. Due to the method which measures and tests the piano technique with the help of sensors, it may provide near-real-time feedback to pianist/piano students about their technique. Sensors installed in a piano can receive subtle information, which piano teachers may not be able to observe on their own. It may also support preventing pianistic injuries. On the other hand, objective explanation of piano playing can make advancing in piano more achievable for adults.

In history, lots of precious knowledge/artifice is lost due to several reasons such as cultural or technological changes, over-conservative keeping, semi-unconscious learning via solely mimicking the masters and oral tradition etc. Science is the most powerful alternative to this extinction. Through objective data provided by scientific experiments, these values can be kept in a situation that never to be extinct but also to be advanced.

The author is in full belief that the expected results that will be derived out of this study are going to be important steps to understand piano playing on an objective basis.

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# APPENDICES

**APPENDIX A:** Technical Details

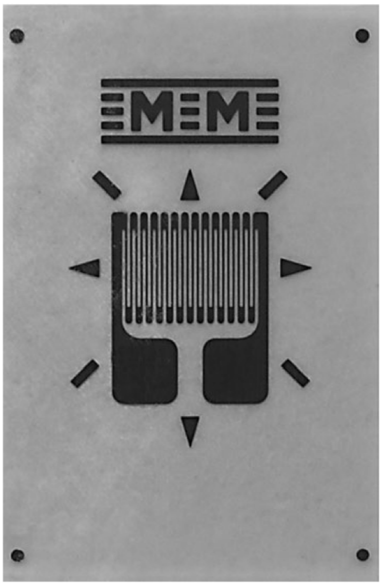
**APPENDIX A:** Technical Details

MICRO MEASUREMENTS
A VPG Brand

**031CE**

## General Purpose Strain Gages—Linear Pattern

**GAGE PATTERN DATA**



actual size

| GAGE DESIGNATION See Note 1, 3 | RESISTANCE (OHMS) See Note 2 | OPTIONS AVAILABLE See Note 3 |
|---|---|---|
| EA-XX-031CE-350 | 350 ± 0.2% | W, E, L, LE, **P** |
| **WA-XX-031CE-350** | 350 ± 0.4% | |
| EP-XX-031CE-350 | 350 ± 0.2% | |
| **SA-XX-031CE-350** | 350 ± 0.4% | |

**DESCRIPTION**

General-purpose high-resistance miniature gage.

**GAGE DIMENSIONS**

**Legend**
ES = Each Section
S = Section (S1 = Section 1)
CP = Complete Pattern
M = Matrix

inch / millimeter

| Gage Length | Overall Length | Grid Width | Overall Width | Matrix Length | Matrix Width |
|---|---|---|---|---|---|
| 0.031 | 0.076 | 0.062 | 0.062 | 0.23 | 0.16 |
| 0.79 | 1.93 | 1.57 | 1.57 | 5.8 | 4.1 |

**GAGE SERIES DATA** — See Gage Series datasheet for complete specifications

| Series | Description | Strain Range | Temperature Range |
|---|---|---|---|
| EA | Constantan foil in combination with a tough, flexible, polyimide backing. | ±3% | –100° to +350°F (–75° to +175°C) |
| WA | Fully encapsulated constantan gages with high-endurance leadwires. | ±2% | –100° to +400°F (–75° to +205°C) |
| EP | Annealed constantan foil with tough, high-elongation polyimide backing. | ±10% | –100° to +400°F (–75° to +205°C) |
| SA | Fully encapsulated constantan gages with solder dots. | ±2% | –100° to +400°F (–75° to +205°C) |

**Note 1:** Insert desired S-T-C number in spaces marked XX.

**Note 2:** Tolerance is increased when Option W, E, SE, LE, or P is specified.

**Note 3:** Products with designations and options shown in **bold** are not RoHS compliant.

Document No.: 11070
Revision: 28-Aug-2015

For technical questions, contact
mm@vpgsensors.com

www.micro-measurements.com
1

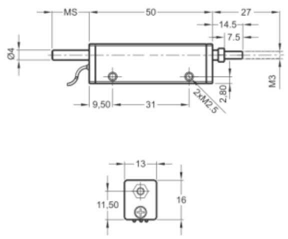
**Figure A.1 :** Strain-gauge sensor specifications.

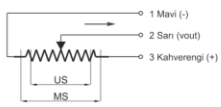
## LMT

### Lineer Potansiyometre
### Ultra İnce Gövde Serisi

- 10 - 25 mm ölçme mesafesi
- Daha ince gövde
- ± %0,05 linearite
- <0.01 mm tekrarlanabilirlik
- Sonsuz çözünürlük

| Teknik Özellikler | |
|---|---|
| Ölçme boyu | 10 ... 25 mm |
| Linearite | ±%0,5 (<75mm) |
| Tekrarlanabilirlik | < 0,01 mm |
| Çözünürlük | Sonsuz |
| Direnç | 2 kOhm, 5 kOhm yada 10 kOhm |
| Direnç toleransı | ± %20 |
| Yük direnci | 100 kOhm min. |
| Tavsiye edilen kontak akımı | 1 µA |
| Maksimum besleme voltajı | 28 VDC max. |
| Elektriksel bağlantı | Kablo çıkışlı |
| Hız | < 5 m/s |
| Mekanik ömür | 50 milyon hareket |
| Gövde ölçüleri | 13x16 mm |
| Gövde malzemesi | Eloksallı alüminyum |
| Mil malzemesi | Paslanmaz çelik |
| Mil çapı | Ø4 mm |
| Mekanik sabitleme | Vida |
| IP koruma sınıfı | IP 63 |
| Çalışma sıcaklığı | -20°C ... +80°C |
| Saklama sıcaklığı | -30°C ... +90°C |




| LMT(mm) | 10 | 14 | 25 |
|---|---|---|---|
| US (Usefull Stroke) | 10 | 14 | 25 |
| MS (Mechanical Stroke) | 12 | 15 | 27 |
| L (Total Length) | 69 | 77 | 89 |

| Model | Ölçme boyu (mm) | Linearite (%) | Direnç (KOhm) | Konnektör / Kablo |
|---|---|---|---|---|
| (örnek) LMT | 25 | D | 5K | 0M15 |
| LMT | 10 ... 25mm | D : ± %0,05 (standart) | 2K : 2 KOhm<br>5K : 5 KOhm<br>10K : 10 KOhm | 0M15 : 0,15 metre kablo (standart)<br>1M : 1 metre kablo |

OP.DS.ver150518

www.opkon.com.tr

Yukarıda verilen teknik datalar sadece bilgi amaçlıdır. OPKON haber verilmeksizin her türlü değişiklik yapma hakkına sahiptir.

**Figure A.2 :** Displacement sensor spesifications.

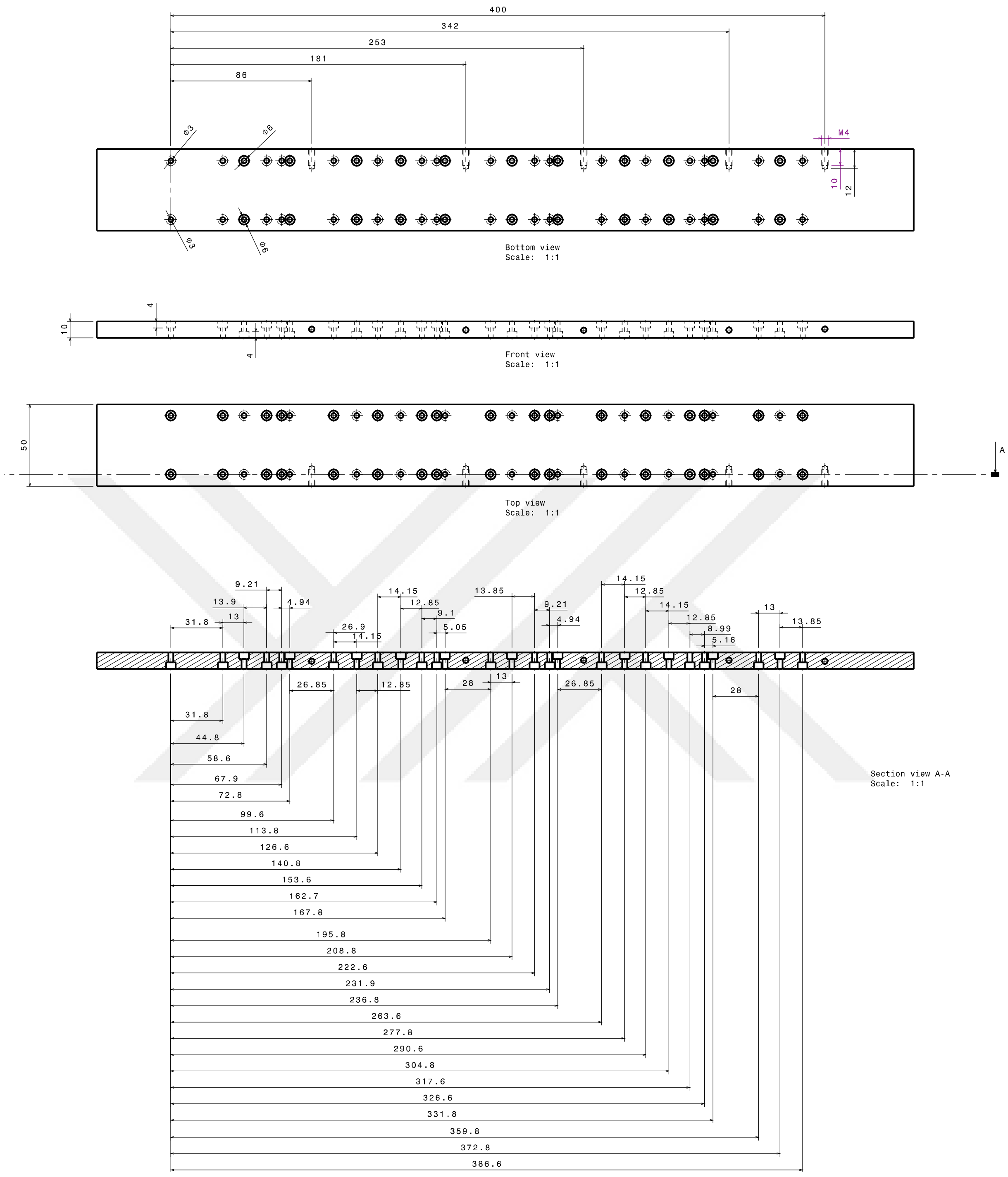
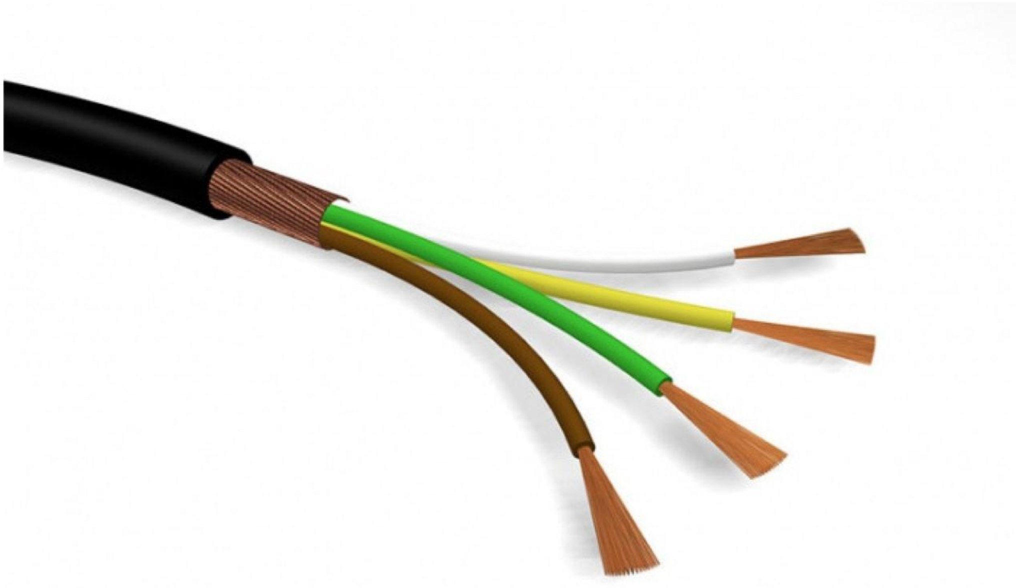



**Figure A.3 :** Installation diagram of displacement sensors.

# Miniatur-Steuerleitungen, höchstflexibel, geschirmt LifYDY



**Verwendung:**

Miniatursteuerleitungen finden ihre Anwendung in Kleinstgeräten, Alarmsystemen, Lichtschranken, Meldesystemen, etc., wo höchste Flexibilität und Störsicherheit bei geringem Außendurchmesser erforderlich ist.

**Aufbau:**

| | |
|---|---|
| Leiter: | 0,05qmm: Cu-Litze, blk. 26x0,05mm |
| | 0,10qmm: Cu-Litze, blk. 51x0,05mm |
| Aderisolation: | PVC nach VDE 0207 |
| Farbcode: | DIN 47100 |
| Verseilung: | Adern in Lagen |
| Abschirmung: | Cu-Wendelschirm, blank |
| Mantel: | S-PVC nach VDE 0207, schwarz |
| Mantelfarbe: | schwarz, RAL 9005 |

**Elektrische Eigenschaften:**

| | |
|---|---|
| Betriebsspannung: | 0,05qmm: 100V |
| | 0,10qmm: 300V |
| Prüfspannung: | 0,05qmm: 500V |
| | 0,10qmm: 900V |

**Figure A.4 :** Cable specifications.

| | |
|---|---|
| Isolationswiderstand: | min. 200MOhm x km bei +20 °C |
| Leiterwiderstand: | 0,05qmm: 400 Ohm/km |
| | 0,10qmm: 200 Ohm/km |
| Temperaturbereich: | ruhend: -20 °C bis +70 °C |
| | bewegt: -5 °C bis + 70 °C |
| Biegeradius: | 10x AD |

**Aufmachung:**

2x0,05 qmm - 8 x 0,05 qmm: Spulen à 250m;
12/16 x 0,05 qmm / 2 x 0,10 qmm - 16 x 0,10 qmm: Spulen à 100m

**Lieferprogramm**

**Miniatur-Steuerleitungen, höchstflexibel, geschirmt LifYDY**

| Bestell-Nr. | Abmessung (qmm) | A-Ø (ca. mm) | Gewicht (kg/km) | Cu.-Gewicht (kg/km) |
|---|---|---|---|---|
| 3402005 | 2x0,05 | 2,7 | 10 | 3,6 |
| 3403005 | 3x0,05 | 2,8 | 12 | 4,7 |
| 3404005 | 4x0,05 | 3,0 | 13 | 5,5 |
| 3405005 | 5x0,05 | 3,2 | 15 | 6,3 |
| 3407005 | 7x0,05 | 3,4 | 18 | 7,6 |
| 3408005 | 8x0,05 | 3,7 | 20 | 8,5 |
| 3412005 | 12x0,05 | 4,4 | 27 | 11,2 |
| 3416005 | 16x0,05 | 4,8 | 40 | 13,6 |
| 3402010 | 2x0,10 | 3,6 | 19 | 7,8 |
| 3403010 | 3x0,10 | 3,7 | 21 | 9,2 |
| 3404010 | 4x0,10 | 4,0 | 25 | 11,4 |
| 3405010 | 5x0,10 | 4,3 | 29 | 13,6 |
| 3407010 | 7x0,10 | 4,6 | 34 | 15,2 |
| 3408010 | 8x0,10 | 4,9 | 37 | 17,0 |
| 3412010 | 12x0,10 | 5,7 | 49 | 22,2 |
| 3416010 | 16x0,10 | 6,3 | 60 | 26,8 |

**Figure A.4 (continued) :** Cable specifications.

## CURRICULUM VITAE

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**PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:**

- **Eren, A. Ç.**, Sünbüloğlu, E., & Buyruklar, A. T. (2021). The Necessity Of Quantitative Approaches In Piano Education. *Eurasian Academy Of Sciences Social Sciences Journal*, *39*, 123–133.
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