THE MONACO TURNTABLE

The revolutionary Monaco Turntable is the first turntable design taking advantage of 21st Century technology for speed control utilizing a Digital Signal Processing (DSP) controller coupled with an active feedback loop to control the actual motion of the platter itself. It is simple and elegant, the true measure of design and engineering excellence. It is painstakingly manufactured and carefully handmade entirely in the USA. It is repeatable to near 100% consistency by each and every owner anywhere. It is simplicity itself to set up and is devoid of any shift in settings over time. Truly a “set and forget” design. Some of the Monaco’s key features are:

- Direct drive with *no mechanical contact* in the horizontal plane. The lowest noise drive and bearing design architecture possible.

- DSP controller with an active feedback loop measures and controls the speed of the platter directly to yield the most consistent and accurate playback possible.

- The DSP control system is checking speed 4,000 times per second (7,200 times each revolution at 33-1/3 and 5,333 times each revolution at 45 RPM) and making corrections as required.

- Speed accuracy of better than .002% from absolute when measured with 3 sigma protocol.

- No Mechanical Contact platter bearing. It is a passive oil immersion hydrodynamic non-mechanical contact bearing. It has absolutely no mechanical contact in the horizontal plane thus, providing the most noise free bearing possible.

- A vertical thrust bearing that is separate and isolated from the spindle bearing and drive system. This ensures rock solid platter control under all conditions. It uses a high tolerance high sphericity silicon nitride ceramic ball riding on a hybrid alloy bearing pad.

- An enormously rigid plinth made of carbon fiber composite coupled with Grand Prix Audio exclusive internal damping. It is truly a 21st Century plinth, high rigidity combined with extraordinary damping in a single structure.

In this paper we will present the actual physical test results showing the behavior and performance of our design. We will demonstrate that the Monaco Turntable is the most speed accurate turntable at any price. This capability makes it the most frequency accurate and therefore pitch accurate turntable with the least playback frequency distortion of any turntable at any price.

We produced a superior design by using fundamentally sound engineering coupled with innovative applications of new technologies that recently became available. By bringing together a team of engineers and companies with proven backgrounds of unrivaled engineering achievements we have established a new level of performance and value in analog turntables that will reset the design standard for high performance analog turntables. The revolutionary design, the ground breaking direct drive system, the most accurate speed control achieved to date, the outstanding industrial design, the list goes on and on substantiating why the Monaco Turntable is the most advanced and technically superior turntable design ever.

Concept

Why did Grand Prix Audio design and produce a turntable? It is similar to our isolation products; we wanted a better turntable for ourselves. After carefully reviewing the marketplace and the technology currently being used we believed it was time for a new approach. The technology did not, in our opinion, properly address several key performance elements. It was apparent that considerable advances were easily possible. Particularly in the area of speed control which is the most important single element of turntable performance. In addition, it fit well with the further growth of Grand Prix Audio by helping to demonstrate our engineering capabilities. We have considerable background in the mechanical design and engineering of high performance machinery and this coupled with our specialty in audio vibration control encouraged us to meet this challenge head on. We then decided to embark upon a multiple year effort to design and manufacture a Grand Prix Audio turntable.

Before we moved toward pursuing this project we established a number of criterion for the way forward. We call these the Grand Prix Audio design protocols. They apply to everything we design.

- **DESIGN FROM A CLEAN SHEET OF PAPER WITH THE PRIMARY FOCUS ON PERFORMANCE.**
- **KEEP THE DESIGN SIMPLE AND ELEGANT WHEREVER POSSIBLE.**
- **DO NOT PERMIT COMMON INDUSTRY PRACTICES TO DICTATE DESIGN DECISIONS.**
- **DO NOT INCLUDE ANY FEATURES, COMPONENTS, OR ELEMENTS THAT DO NOT DIRECTLY CONTRIBUTE TO PERFORMANCE AND/OR VALUE.**
- **REMAIN AWARE THAT DESIGNS BASED ON IMPROPER THEORY WILL YIELD INFERIOR RESULTS, NO MATTER HOW SOPHISTICATED THE EXECUTION, WHEN COMPARED TO DESIGNS USING PROPER THEORY EXECUTED SIMPLY AND WELL.**

This is our company philosophy and our way of doing business. No nonsense or marketing doublespeak. Just straight talk backed up by provable performance.

Research

The first steps before beginning the design process are research to define the current state-of-the-art and then to establish initial performance goals and the potential methodologies for the design. This would also help us to identify how best to test and develop this design and thus be able to confirm that we have achieved our design goals.

During the research portion of the program we reviewed the design of turntables past and present. We carefully studied the individual elements of these designs to determine their importance and how each one fit in the overall design. There have been many good sounding turntables ranging from modestly priced designs to limited production exotics. Some with suspended designs and many without suspension. Some independently exclaimed to be standard bearers, others simply run of the mill. All but for a few were variations on the basic belt drive architecture with high mass being the fundamental design element. The upper regions of this design theme were super high-end designs tending to represent the least design efficacy relative to cost. The general design theme among these being to make it bigger, heavier, fancier, more complicated and, seemingly, to make it look as expensive as possible. All this, sadly, while maintaining the same fundamentally flawed core elements, inferior materials, belt drives, high mass, poor performing suspension, and complicated features which, at best, deliver questionable performance improvements.

- We studied the industry standard testing protocols for evaluation of a turntable design and the specifications these tests generate. Our experience is, that if you cannot reliably test what you have engineered and developed, you cannot actually know what you have when you are finished.
- We researched the manufacturing process for vinyl records, and the standards and specifications to which these records are produced and engineered. We also investigated the various types and performance specifications for the cutting lathes used worldwide to make master records, including their speed accuracy and rumble specifications. We learned many interesting and surprising things during this process:
    - It must be understood that record grooves contain only amplitude information and no frequency information. The frequency information of the record is generated by the speed turned by the playback device. Any deviations, changes or errors in the speed accuracy during playback will change the pitch of the signal retrieved by altering its recorded frequency. Simple fact, the more accurately you turn the record the more accurate the frequency/pitch reproduced and hence the lower the level of distortion and the greater the level of realism. This is why we viewed superior speed control essential to assuring superior playback performance.
    - The most acclaimed designs in both cutting lathe and playback turntables had one thing in common; they featured direct drive.

We were shocked…the industry has so maligned direct drive that a person would be lead to believe that you just do not make good sound without a belt drive and big, bulky, heavy, and complicated contraptions. With careful study of the problem one quickly learns a very different lesson. In fact, belt drive is a hopelessly flawed method of turning a platter, because it cannot maintain a constant and perfect speed. This may be the reason the state-of-the-art in turntables has remained underdeveloped and far from its zenith even after more than 50 years. The designers keep trying to make a fundamentally flawed design do something it simply cannot, which is to deliver a highly consistent and accurate platter speed. The current turntable designs simply do not maintain a consistent speed when measured at the platter.

Belt drive evolved because proper direct drive was too expensive to be produced for consumer use and direct drive was only used on the best radio station professional turntables and on cutting lathes to master records. Direct drive designs became the cheapest way to produce inexpensive turntables for the masses but not the best sonic solution at the time. This created a false impression of the actual core virtues of direct drive versus belt drive. Comparatively, the belt isolated the platter from the excessive noise of poorly designed cheaply made direct drive systems and was simple and inexpensive to design and produce. Today the belt drive design architecture has been fully developed and maximum levels of performance were found years ago. Presently many turntables are much quieter than the records played upon them even with the belt making noise directly upon the platter. This is an area where most designs are already performing reasonably well; noise is obviously not the most significant element of playback performance any longer. While there is always room for improvement, we believe our mechanical design to be the quietest yet but it also became apparent early on that the focus should be placed on improving speed control.

By using enormous platter mass in an attempt to smooth out the unavoidable oscillations in belt drives manufacturers achieved better sound but this still retained the fundamental flaws. One of the significant tradeoffs with high mass platters is that more torque is required from the motor to maintain motion. While mass is being used for its flywheel effect, smoothing out the hit of each addition of energy and the subsequent stretching and slacking of the drive belt and thereby reducing the resulting oscillations in the platter motion, there is a negative side effect. The mass itself must be kept in motion. The larger mass requires more energy to maintain its motion and so on and so on. The cycle repeats. Larger mass has reduced these negatives to lower and lower levels but these designs still offer only a reduction in the inherent behavior not the elimination of it. Further, in these designs (and in some inferior direct drive designs) the speed is controlled exclusively via measurement and control of the motor only. While this might yield some degree of control over the motor itself it does not directly correlate to control of the motion of the platter. There are several reasons for this total disconnect in behavior. First, the platter is in essence disconnected from direct control by the motor. The connection is made via a flexible link. This link, no matter its type, will change its dimension when load is applied to it in the process of moving the platter. As Newton stated, an applied force will give an equal and opposite reaction and thus the platter speed will oscillate. However, let’s for one minute suspend reason and believe this fundamental behavior can through some magic be eliminated, then what? The next issue will become dimensional accuracy of all the drive system parts including the belt. Unfortunately, it is extremely difficult to produce pulleys and especially a belt groove on the platter with the final installed dimensional and concentricity tolerance levels necessary to ensure that there are no cyclic speed errors and to deliver the extreme speed accuracy that is required. To do so would require dimensional control of the drive system at the level of optical mirrors. Even more difficult is manufacturing a drive belt of any type that will have adequately precise diameters to a tolerance level necessary to ensure extremely accurate platter movement. Worse yet, the belt will change size when load is applied changing its diameter and continually creating speed errors. You can see the endless loop of compromise that exists in the belt drive high mass designs.

These days there are several belt drive variations proclaiming to be the best turntable in the world, are they really? None of them measure or control the speed of the platter itself. None of them can demonstrate the actual performance and behavior of the most key element of any turntable design, the speed and rotational behavior of the platter.

Still, a few clever engineers have produced direct drive designs that were markedly superior. Sadly, due to the state of technology at the time these designs were price prohibitive to all but a handful of extremely wealthy vinyl enthusiasts. Experts in this field have accepted the direct drive design architecture as the superior configuration for a long time.

Lastly, and most importantly we should review the methodology used for speed measurement and noise measurement. In order to properly engineer anything one must understand what needs to be done, decide how to best achieve this, and then to test and confirm that this can be achieved by the final design. This type of testing will guide your design and development and will allow you to determine if you have met your goals. Further, while we felt that certain improvements in design would be audible we had no proof of this. Thus we would need a reliable test methodology for certain elements of performance to determine if the improvements made would indeed be truly audible.

There are two important aspects of speed control: the absolute speed, which ensures perfect pitch and tempo and short-term speed accuracy, which minimizes wow + flutter and the subtle nuances of soundstage and image performance. To better understand this let's look at a single platter revolution, assuming that it will be repeated each time around. Optimal performance would be a platter that turns at precisely 33 1/3 (or 45 rpm) at every moment within each and every revolution. This means that if you sliced a single revolution into 1,000 sections the speed would never vary even within a single slice. Thus, if you measured the time it takes for the stylus to traverse the distance from point A to point B on each of the 1,000 individual slices of each and every revolution, every time period would be identical. This would be optimal. Our goal will be to approach this optimum as closely as possible.

It also became apparent that a key issue would be defining and measuring the speed error itself. In order to study the platter behavior and speed accuracy it would be absolutely essential to measure the platter speed directly. Belt drives have an oscillating link between the motor and the platter thus the platter does not do what the motor does. Likewise, direct drive designs that measure only motor speed cannot insure similar control of the platter. If you are not measuring the platter directly you cannot know what is actually occurring during playback…that is an unavoidable fact! This is why the Grand Prix Audio Monaco Turntable measures and controls speed via the platter itself.

Our research and review made it clear that achieving superior speed control and much lower noise would only be possible with a unique direct drive approach.

Another aspect of turntable performance is its perceived "coloration". Coloration is a subjective term used to describe or characterize some turntables as warm or lush, while others were perhaps defined as sterile or analytical. Why would some turntables have certain colorations and what could be the cause of this? Why would the same record sound different on two different turntables? A significant contribution to coloration is probably in the combined characteristics of the tone arm, its wires and the cartridge. However, many tables are defined as having the sonic colorations regardless of the arm used. It is well known that internal resonances can be an influence, especially in poorly executed designs. Choice of materials can also have an effect.

However, after careful review one comes to the conclusion that coloration is probably based largely on the quality of speed control. The speed with which the record is turned will indeed affect its pitch/tone and can easily make one sound warm while another sounds sterile all simply because of the speed and accuracy to which the record is being turned. Of course, this "cause and effect" relationship is difficult to solidly establish; it can only be assessed intuitively. We endeavored to create tests that would give us a more solid method of evaluation. We manipulated a belt drive turntable such that we could affect its speed to small degrees both overall and randomly and indeed this was readily audible. Most analog users understand this and have experience with this. When they select different pulley grooves to shift overall speed faster or slower this affects pitch and it is easily audible. At this early stage, this gave us the confidence that working toward a higher level of speed control would yield a significant improvement in playback sonics. We established a plan during this period to develop a test rig turntable to enable further testing along this line as early in the project as possible.

Design

After much research, and the review of current existing designs, we concluded that the most important aspects of a turntable design, in order of importance, are as follows:

- **THE ACCURACY AND CONTROL OF PLATTER SPEED.**
- **MINIMAL NOISE GENERATION (BEARING PERFORMANCE & ISOLATION ARE COMPONENTS OF THIS)**
- **OPTIMAL DYNAMIC BEHAVIOR AND DAMPING OF THE PLINTH AND TONE ARM MOUNT STRUCTURE**
- **AESTHETICS AND EASE OF USE**
- **PRODUCABILTY OF THE DESIGN**
- **COST AND MARKETABILTY OF THE FINISHED PRODUCT**

The single most critical element of any turntable's performance is the platter speed control. The more accurate the platter speed control the more accurate the frequency reproduction of the turntable. Imagine if you lightly drag your finger on the platter and slightly affect the speed. What do you hear? You hear a change in pitch. This is what frequently occurs during each revolution with a belt drive.

Unlike the electronics that we commonly use, turntables are mechanical devices and the comparative performance of these devices can be reasonably, if not absolutely in many cases, estimated through measurements and specifications. This is where we were once again surprised. The few specifications we could find for contemporary turntable designs indicated they were incredibly poor when it came to speed control. It was obvious we could engineer a better, more accurate drive system and it was clear that it would have to be direct drive if it was to achieve the high levels of speed accuracy we desired. Further, we would need to develop a more precise test method to determine if the improved speed accuracy and the subsequent reduction of wow and flutter would be audible.

While this project was intended to be a technical demonstrator it would be a failure if the resulting device was so costly to produce that only an elite few would ever experience its performance. For Grand Prix Audio it would be a far more challenging and rewarding goal to define the state-of-the-art and do it with engineering that was practical, effective and elegant and would not, therefore, cost stratospheric amounts of money. Our turntable did not have to be cheap but it had to represent excellent value for dollar. It had to represent a value beyond any other offering at any price when performance was the number one consideration. This would represent a true advancement in the state of turntable design.

We needed to specify and set the design goals. Our design goal for the drive system was a speed accuracy level, measured at the platter, while playing a record, in excess of 20 parts per million even when measured within a single revolution. In other words platter speed would not vary by more than .002% from absolute even when measured directly at the platter over time or within a single revolution. This variation would be defined using three sigma protocols* as opposed to the typical RMS method**. Measuring the accuracy not only over time but also within any single revolution gives the most precise overall view of the true speed accuracy of the design that is obtainable. For reference, this compares to the current best quote of speed accuracy at any price of .005% RMS, which represents a speed error 3.5 times greater than our stated goal of .002% peak error from absolute. Further, no other turntable manufacturer measures the actual speed of the platter. Instead they measure the motor speed and infer the platter speed from that. This will subsequently conceal the speed errors in the drive system.

This accuracy had to come in a drive system that was free of mechanical noise beyond the best turntables. This task was made easier by not having a belt drive producing noise by rubbing directly upon the platter. We would, however, require an innovative bearing design. Our goal would be to ensure *NO MECHANICAL CONTACT* between the bearing system and the platter.

The plinth will have to be resonance free under all operating conditions and be of enormous rigidity to provide adequate support to the bearing and platter assembly, while providing exceptional damping. The overall functionality and appearance had to be of a generally superior level. It must be easy to use and easy to set up, trouble free and simple in every way. This would best ensure that each and every owner would be delivered a product that will consistently yield the superior performance expected from our design. It will feature push button speed change and push button speed trim adjustments in very finite and accurate percentages of .2%. The trim adjustment will allow compensation for recordings that were produced slightly off pitch. There will be no requirement or need for external components of any type other than the control module. Welcome to the 21st Century!

*3 sigma means 997 times out of a 1,000.

**RMS is an average measurement that conceals the small variations by averaging them into a long-term measurement. This hides the flaws of a drive system as it relates to the precision and consistency of turning a record. Thus even a table with a claimed speed accuracy of say .005% RMS is still generating individual speed errors much higher than this but they are averaged out.

The Way Forward

We were fortunate that when we began to get serious about this project, the advance of technology had opened doors of opportunity for us that until 2003 did not exist. Our research showed that recent advances had been made in motor technology and motion control technology that would enable a new state-of-the-art direct drive speed control to be engineered. With this bit of data and an understanding of the limitations of existing devices, we took the decision to move forward with the design a new state-of-the-art turntable.

Building the Team

Grand Prix Audio has an extensive history of involvement in the design and manufacture of mechanical systems that dwarf in complexity any turntable ever made. Bold as that declaration may be it is still a comparatively modest statement. Not only have many of the engineering projects in which we have been involved been far more complex but they also have a record of proven superior performance. Nevertheless, this project and its design goals would clearly require the involvement of others if we were to succeed. I needed look no farther than my own background for a mechanical design partner. Our design partner designed and engineered entire racing cars from the gearbox to the brake system, from the cockpit and safety systems to the aerodynamics and structural composites. Our primary mechanical design partner on the turntable project is: David Bruns.

We worked together in racing for many years. David is the designer of many of the racing cars I have been involved with during my time in auto racing. We most recently worked together at Swift Engineering on the Swift Wind Tunnel, the Swift Indy Car and other automotive projects. The Indy Car was the only American effort in nearly 20 years to win races and be viewed by those in the industry as a technologically superior design. These were David's designs. He even designed the wind tunnel used to test and develop the cars! David's wind tunnel design was considered the best in the world for many years and was used by Williams Formula One and other F-1 teams, NASCAR teams, major auto manufacturers such as BMW, and aerospace companies such as Boeing. We think that this is a proven record of engineering excellence few can rival. David has accomplished much more than this but we feel this is more than enough to make our point.

We are very accustomed to evaluating current standard methods and then, if they prove inadequate for our purpose, develop our own path as a better way. We have done so before working together on racing car projects. We do not feel constrained by established practices if we are confident it will help us outperform our competition. We are accustomed to doing these types of large undertakings with extraordinarily talented engineers and dedicated industrial partners. We know from experience that the same processes that can design a winning Indy Car can be applied to producing a winning turntable.

A pivotal requirement would be design partners who could help us with the critical drive and motion control elements we considered fundamental to a superior result. We searched the world, literally, looking for electrical engineers and software engineers with the experience and knowledge to get the job done. Once again our racing background paid off. In speaking with one of the key engineers who wrote the software for the control system of the Swift Engineering high speed moving ground plane wind tunnel we learned of an electrical engineer who had provided significant and advanced work for several major electronics companies.

We were fortunate to secure the participation of Vince Capizzo, founder of Midnight Designs, as our electrical engineering partner. Vince started the research and development segment of his electronic engineering career with Solid State Logic (SSL) in the UK. At SSL (a world leader in recording consoles) Vince did the hardware design for their machine synchronizer system, which locked video and multi-track audio machines together to within 1/100 of a frame, for perfect lip-sync. He designed the video switcher in their Total Recall ™ studio automation system. He also designed the bargraph metering system for SSL's console. The meter system also involved design of a 1/3-octave audio spectrum analyzer, for which 32-channel meters of the console displayed the frequency spectrum of the program from 20Hz to 20 KHz. The plasma display was also an opportunity to learn about noise/interference reduction techniques. The plasma elements require that a +260V signal be switched on and off about 100 times a second. This high-voltage switching was within inches of the microphone preamps and had to be made absolutely quiet. Approaches Vince learned there have had applications even up to the present day.

After 3 years with SSL, Vince became VP of Engineering at Producers Color Service, a company with video production and editing facilities, multi-track audio mixing, motion picture film lab and a CD mastering and manufacturing plant. He built 3 state-of-the-art audio mix-to-picture rooms there. He also did the optical, mechanical and electronics design for a high-def color laser film recorder to scan HDTV on to 35mm film. It used 3 color lasers, and a high-speed (81,000 RPM) air-bearing optical scanner to write the images to film in real time. During this period, he also served on the SMPTE HDTV standards committee, and received a patent for a video motion detection system. After Producers Color, Vince hooked up with Dan Lavry and Bruce Jackson of Apogee Electronics doing logic design for Kodak's "Cinema Digital Sound" project, and for Apogee's groundbreaking AD-500 A/D Converter. In 1994 Vince incorporated as Midnight Designs, designing a custom 20-bit modular multi channel ADC (< 0.008% THD) for Dorian Recordings. This caught the attention of David Smith, head of technical operations at Sony Classical Recordings and he then produced several designs for Sony. Other projects include the ProSound digital converters for Lightworks Editing Systems. Vince also, designed and manufactures a Digital Audio Format Translator, favored by Bernie Grundman, and used in CD mastering worldwide. Most of you listen to recordings using Vince's designs in their production process. Well, that's a lot to write about but we believe it is important you know the background of the engineers involved and their past achievements as it speaks to ability and integrity.

With the participation of these team members secured we then worked on finding our industrial partners. We made inquires worldwide for a suitable supplier of the state-of-the-art low speed motion control system that would be required to advance the vinyl turntable to 21st Century performance levels. After about a year we found a company that had the background and engineering talent to do it. In early conversations they acknowledged that the state-of-the-art in low speed motion control was not on a par with the more common high-speed applications and indeed advances were likely possible. This partner was interested because they saw industrial applications that had profit potential outside audio. We made a contractual agreement of proprietary control for the audio industry and began moving forward with the design process.

Lastly, we needed to find a motor manufacturer that was willing to participate and then to develop a special motor to suit our design. Fortunately our industrial partner for the speed control project knew of a likely candidate. They introduced us to our motor engineering partner who has a background in supplying specialty motors for motion control applications such as those used in the manufacture of computer chips. The company had an on-the-shelf design incorporating a new motor technology that could be modified to provide a prototype for our development program. The motor and controller could then be optimized to meet our specification for the final design. With the team put together we started down the long path to achieving our design goals.

The Drive System

We started with the basic design for the drive system and platter bearing. This preliminary design was incorporated into a turntable test rig that would be used to evaluate and develop not only the drive system and bearing but also to develop the control system software. It would also be used to define the platter mass requirements and give an initial look at wow, flutter and rumble performance. It would also be used to confirm that the speed accuracy improvements were indeed audible. The test rig would allow us to evaluate and develop the performance of the individual components as well as how those components integrate into the complete system.

The drive system uses a Digital Signal Processing (DSP) controller coupled to an optically encoded feed back loop to monitor and control the motor. It features an encoder disc with over 4,700 individual lines. The DSP system makes individual speed measurements and speed adjustments (if required) over 4,000 times a second. The system makes extremely sensitive adjustments to the energy being feed to the motor in a way that will maintain unparalleled speed accuracy. The system operates on a nominal 5 volts DC.

We needed a very unique motor to fit our proposed design. We found a suitable motor configuration in the high tech world of computer chip manufacturing where motion control on the order of tenths of thousandths of an inch is an every day reality. Our motors were derived from these applications and are manufactured and hand wound to our specification and are made in the USA. The DC motor has 12 poles with a high tech ceramic magnet rotor and incorporates Hall sensors. Because the DSP controller knows the position of the rotor relative to the stator at any point in its rotation (via the Hall sensors) it can commutate the motor in a manner that eliminates any torque variation as the magnets pass from pole to pole. The result is a running motor that is dead smooth; all 'notching' has been eliminated.

The encoder disc is attached to a high precision (+/- .0005") machined surface beneath the platter. The disc runs through the optical encoder module that reads each of the over 4,700 lines positioned on the outer edge of the disc. There is no physical contact between the disc and the encoder module. The DSP controller calculates the speed of the platter based upon the elapsed time between each passing line on the disc and then feeds the motor the appropriate amount of energy to maintain the set speed. Because the motor rotor, the encoder disc and the platter are all combined into one rigid assembly the controller is able to directly maintain the highly accurate and highly consistent rotational speed required by the platter. It is important to note that using this approach we don't just *drive* the platter, we *control* the platter. This level of precise platter speed control would be impossible with any other type of drive system.

The Control Computer

The heart of the Monaco Turntable is the unique drive system. Its soul is the computer control module. It is the DSP processing which occurs inside this module that makes this extraordinary speed control possible. The DSP controller runs at 40 million instructions per second (40 MIPS) and is specifically optimized for precision motor control applications. The control module receives and processes the encoder signal and adjusts platter speed, as needed, over 4,000 times per second. The control module interface features the power on/off button, the speed select switches for 33 1/3 and 45 rpm, and the speed trim and display that allow for adjustment of the set speed in increments of .2% in 5 steps above or below the nominal speed setting.

The power cord is installed into a socket on the control module. An umbilical cable leads from the control module to a 16 pin Lemo connector termination. This is plugged directly into the female Lemo connector in the turntable plinth. The control system is factory upgradeable by laptop computer enabling future potential performance updates.

The Bearing

We would need to ensure the drive system is adequately isolated from the platter stylus interface. This would require a different approach to the bearing design. There are two loads to consider; the vertical thrust load required to support the mass of the platter (including the stylus load) and also and more critical the horizontal rotational loads of the platter and drive system. The common platter bearing design is high tolerance bushings and shaft type bearings. Unfortunately, even the most carefully manufactured version of this bearing will have mechanical contact and thus noise and friction.

We concluded that the best way to solve this problem was to immerse the entire platter spindle/bearing assembly in an oil bath. This would allow a film of high pressure oil to develop that would eliminate any mechanical contact. In this design we use the motion of the platter itself to create the pressure required to support the spindle. The motion of the platter spindle in the bearing creates adequate oil pressure in the close tolerance assembly to separate the platter from the spindle bearing with a cushion of oil. This also offers extraordinary damping. The oil volume is constantly in circulation from the base of the spindle bearing up the shaft and out the top to fall by gravity back to the sump below. We found this to be the most elegant solution to the bearing problem. Simple, elegant, and absolutely optimal, it ensures *NO MECHNICAL CONTACT* in the horizontal plane whatsoever by any components. Further, it is maintenance free and requires no special set up. It is simplicity itself. Nothing can be quieter than no mechanical contact, nothing. It also offers extremely favorable damping and energy management compared to more complicated approaches. Superior engineering allows us to achieve a better result with less cost and complexity.

The platter spindle is a high alloy stainless steel shaft that rides in the solid single piece phosphor bronze bearing / mount structure. The vertical thrust load is carried on a coaxially located high precision silicon nitride ceramic ball bearing that rides on a bearing pad made of a proprietary hybrid alloy. A damped support rod, independent from the platter bearing and spindle, provides vertical support for this assembly. The thrust bearing assembly and support shaft are also fully immersed in oil.

This drive system and bearing design were tested over many months and the software and circuitry were perfected until the worst error in speed during an hour of running never exceeded .002%. Please keep in mind this is 14,400,000 individual measurements in one hour and never does the platter speed vary more than .002% from the set point. In reality, the system actually is much more accurate than we claim. In actual operation the system generates one error per half hour of .0019% and once every 15 minutes of .0015%. *These are statistical intervals and the error is actually random but calculates as stated above.*

The Platter

The requirements for our platter design are unique and are different from existing turntable designs. For this reason we consider the platter design to be highly proprietary. We are willing to discuss some aspects of this design and to that level we will detail some of these design features.

Our drive system design does not require a large mass because the drive system is inherently stable and accurate by itself. Thus large amounts of inertia and mass are not needed to manage speed stability. Speed accuracy is ensured by means other than flywheel effect. It is also true that a large mass is not required to manage the energy of the stylus upon the record. Adding more mass will not improve speed accuracy; it simply makes no difference beyond a certain point with our type of drive system. This, of course, gives us a huge design advantage in that we can now do things that would not be possible with a massive platter. The elegant, less massive, design that is now possible will also allow much better energy management. The lower mass platter will also require much less power to maintain speed.

Having a lower mass requirement enabled us to make a high performance platter machined from one solid piece of high silicon alloy magnesium billet. The platter requires dimensional tolerances beyond .0005” (one half a thousandth of an inch) in some areas. This is due to the specific nature of a drive system and bearing system that require extraordinary assembly tolerances to achieve the level of precise operation we need. The specific details of the platter are proprietary but it was designed to provide for very precise stylus tracking relative to the record groove. It has inherently beneficial damping properties due to its alloy and these are enhanced with the external application of other materials.

The platter assembly also incorporates an internal balance wheel made from phosphor bronze. This material was chosen for its high density among other mechanical properties. The primary function of the balance wheel is to position the center of gravity of the platter at the proper location relative to the thrust bearing. This location for the center of gravity provides the inherent platter stability needed to create an extremely low noise and dynamically stable drive system. The balance wheel also contributes to the required total platter inertia and aids in damping the platter.

As part of the platter design, we studied various record mats, plastics and other material interfaces that might be used under the record and found that the majority of these approaches yielded measurably worse levels of rumble. While some will argue that platter impedance must match record impedance in order to achieve optimal performance, we can say that this is clearly not the case. The primary requirement of the platter is that it does not allow any deflection of the record. Ideally the platter should be infinitely rigid. This will ensure that the stylus can track the exact information contained in the recorded groove and also ensure that the record cannot resonate, as its surface is clamped against the platter. The platter natural frequency is well above a level that would be excitable by the record, making impedance matching irrelevant.

The Plinth

All this fantastic modern drive system and bearing technology must be supported and packaged. To achieve the ultimate structure for a turntable plinth we took advantage of our unique experience with highly rigid composite structures and our expertise in vibration control to make the world’s best and most sophisticated plinth.

Composites offer significant design opportunities simply not possible with other materials, metals or alloys. With our considerable experience in composite structures this was our clear choice. The turntable plinth application requires that the material must be as rigid as possible while still exhibiting extremely favorable damping properties. This difficult combination can be found with structural composites like no other material. We can design a hollow structure with shapes and thickness variations as dictated by the design requirements. We can then fill this hollow core with vibration damping materials that will manage energy vastly better than possible with any other type structure. Achieving these unique characteristics would not be practical or perhaps even possible with metals, plastics, wood, etc. Further, we can avoid the old boxy shapes and are free to incorporate pleasing designs that provide higher rigidity as well as much better aesthetics. The strength of this very unique structure is unparalleled while having damping properties superior to any metal alloy.

The Monaco Turntable plinth is constructed from solid laminate of carbon fiber cloth pre-impregnated with toughened epoxy resins. This carbon “pre-preg” material is the same type used in Formula One cars and jet fighters. The carbon pre-preg cloth is as many as 20 layers thick and is applied in various directions, to best take advantage of its properties. It is laminated into a highly polished, high precision solid aluminum mold. This is then cured at 250 degrees Fahrenheit and 250psi while under vacuum. Each individual plinth structure takes several days to construct. It is comprised of separate upper and lower sections that are bonded together with internal hard point features. It is filled with a proprietary polymer combination to improve its energy attenuation. The completed structural assembly is then CNC machined to exacting tolerances in excess of +/- .001”.

Our plinth is unrivalled in its unique combination of strength, stiffness and damping properties.

The Tone Arm Mount

We decided that it was important that our customers be able to use the different available tone arm designs. Many current offerings are well engineered and well made and represent the choice of several different design types. We felt that this was an area where options would be important to the end user. Therefore, we needed our tone arm mounting to be not only extremely rigid but also easily changeable by the owner. Again, the nature of our composite plinth structure allowed this to happen. We are able to mold in the appropriate shape to provide a support area for the arm board which features high stiffness and therefore a high natural frequency. The arm board is actually inserted up inside the plinth to nearly its center and then secured by six bolts that penetrate the plinth from below and then through specially designed and constructed isolated internal hard points and then into the arm board structure. This accomplished the design goal of a superior tone arm mounting structure while maintaining the capability for the user to easily reconfigure for alternate tone arms in just minutes.

The Support Feet

We made an early design decision to keep the design simple in every way. This meant a no suspension design. We fiddled with suspension a little bit early on in the design process but ultimately decided that trying to properly suspend the turntable itself was not the right way to go. It became apparent that adding a suspension system would create many more potential problems than it would solve and at the same time would add unwarranted complexity and cost to the final product. Instead we designed the turntable with a very stiff and damped structure and planned for it to be used on a quality isolation stand such as our Monaco Modular Isolation System. We focused on the quality of the support structure/plinth and the feet. As in our other designs a ‘three point’ support system would be used for its stability and freedom from resonance due to the uniformity of loading. The principle that “three points define a plane” is why all sensitive support structures that require stability, such as camera and telescope tripods, etc., are always three points.

Again, the design advantages of composites allowed us to place the feet were they would provide maximum performance and ease of use. The required shape and reinforcement of the structure was easily designed into the composite plinth to make the location of the feet a matter of choice rather than a constraint on design. The rear foot is located directly under the tone arm mounting structure for a specific reason. This area must not be left to potentially resonate as part of an unsupported or loosely affixed structure.

Between the plinth and the top of each foot is a silicon nitride ball. This ball allows each foot to align correctly to its local surface assuring correct support. The bottom of each foot features a layer of Sorbothane of the correct specification to reduce any energy that may be reaching the turntable. It also has a low friction plastic interface to allow for movement of the turntable on the shelf. Each front foot adjuster is equipped with a precision stainless steel “ultra fine thread” level adjustment. This allows for the precise leveling of the table that would have been difficult with standard threads. It’s the little unnoticed and unthought-of details like this that add to our advantage over other designs.

The Record Clamping System

Here is a controversial area. There seems to be a great deal of dubious philosophy and doctrine in regards to record clamping. Some people want to see vacuum type clamping systems on high level vinyl turntables. Some people want to see outside diameter clamps and/or mass center clamps. We were only concerned with performance and thus we carefully reviewed not only vacuum clamping but also all methods of mechanical clamping.

We chose not to use vacuum clamping. This was not because we believed it would be too costly. We had no limitations on costing that would preclude incorporating a vacuum type clamping system. In making this design decision the single most significant reason for not choosing a vacuum hold down system is simply put in one word, SEALS. If you chose to have a vacuum hold down system then you chose to have seals and you therefore chose to add some amount of noise to the overall system. We decided early in the design process to put more weight toward noise elimination than any other design issue after speed control. Further, after testing what was possible with our version of mechanical clamping we became convinced that any possible performance delta between the two methods was not enough to warrant the negative elements of the seals, their subsequent noise, and the additional equipment and cost required. Another issue facing vacuum system users is that, depending on the altitude of their location, there will be differing levels of clamping pressure. This can result in a significant difference in clamping force that will affect the overall performance of the turntable. This type of variation would make it extremely difficult to assure that each owner would be able to achieve the same high level of performance that we intend to provide.

A mechanical clamping system was the choice we made for our design. We arrived at this decision after carefully testing several mechanical clamping methods. We rejected the O.D. clamp as unnecessary and undesirable early in the design study. No matter how they are executed the O.D. clamp can introduce potential eccentricity problems to the bearing and platter assembly and thus potentially cause degradation of a carefully designed and balanced assembly. Another problem was that some popular cartridges did not have adequate ride height to allow the use of even a very thin lip on the outside clamp. We concluded that, if the record were properly clamped in the center using our method, the outer clamp ring would offer no improvement.

We chose to bring the tried and true center clamp to a higher performance level. We did this by adding a visco elastic Belleville washer under the record center. The record is then tightened to a predetermined torque and the washer deformation ensures not only full contact between record and platter from outer edge to center but it also attenuates unwanted resonance from the record. This insures that the stylus will play back only the information found in the record groove with no additional noise from resonance within the record itself. When the record is placed upon the visco elastic center damper it is held off the platter by approximately .125”. As the clamp is tightened, the outer edge of the record is forced down to the platter first. As the clamping torque is increased further, the remainder of the playing surface is forced into contact with the platter surface. With the record fully clamped, its center is cone-shaped and is being damped by a properly compressed visco elastic damper. The contact pressure of the record to the platter is positive throughout.

Mechanical clamping is much easier to use, there is no maintenance, no susceptibility to over clamping, and best yet, there is zero noise. In addition, you will hear no cycling vacuum pump and you have no seals putting vibrations into the spindle bearing; nothing is simpler.

Measurements and Testing

In this section you will find important information about measurement and testing as well as factual data from actual tests of the Monaco. As stated before, we believe that the behavior of the platter itself is the single most critical performance element of any turntable. The speed accuracy of a turntable has typically been defined using the RMS or “root mean squared” method, which represents an average measurement. The idea is that you take the data (which is positive and negative around some average) and square it. Squaring makes all the data positive. Then you take the mean (the average) of the data, and then take the square root of that. For these purposes, an RMS reading is the peak reading divided by 1.4. That is; 0.002% peak equals 0.0014% RMS; 0.001% peak equals 0.0007% RMS, etc.

Thus a turntable with a claimed speed accuracy of .02% RMS has an average error over about an hour of .02%. This of course minimizes the severity of any single error as it was simply averaged in. We do not use RMS to define our speed accuracy and we will explain why. For comparison if we defined the performance of our turntable using the old RMS standard we could say we are .0014% accurate versus the average industry claim of .02% and the best claim known of .005%. We do not use this (RMS speed measurement) because it masks the reality of the true speed accuracy of a design. It simply is too crude when compared to the standards available today for describing the speed behavior of the platter.

The performance of a turntable can be fundamentally defined by 3 parameters of performance:

Speed of rotation, Weighted wow & flutter, Signal to rumble ratio.

The dictionary definitions of flutter and wow are as follows; Audio definition of Flutter: a variation in pitch resulting from rapid fluctuations in the speed of a recording; Audio definition of Wow: a slow wavering of pitch in sound recording or reproducing equipment caused by uneven speed of the turntable or the tape.

Fundamentally, both wow and flutter are just a measure of tolerance on the basic platter speed.

Rumble is tougher to quantify. It is a number given to the amount of vibration imparted to the stylus caused by the motor, belts, bearings, turntable suspension, the platter, the environment around the table, and the test record, as measured while playing a silent groove. It’s relatively easy to get a rumble number, but it is very difficult to get a number that actually means anything.

When you see a rumble spec, it’s a negative dB figure, say, -80dB. This number may look great, but it doesn’t say anything about how it was determined, which is critical. For example, it doesn’t say what the figure is 80dB down FROM! Is it relative to a reference of 5cm/sec at 1 KHz? 10cm/sec at 315Hz? That depends on the Standard it was measured to, which is seldom if ever quoted. There is also the question of whether the rumble number is weighted or un-weighted. Weighting refers to the portion of the spectrum, audible or sub-sonic, over which the measurement was made. It specifies the “bandwidth” of the measurement and also the frequency at which the measurement is most sensitive. Different standards have various weighting requirements. Another factor is the “variableness” of rumble. It is not constant.

The mechanical irregularities or ambient vibrations contributing to rumble have differing periodicities, and add up in a random way. This means the rumble meter, whether a mechanical needle or a digital reading, bounces around during the measurement. How do you interpret that objectively? The obvious way is by averaging, but, again, different standards specify different meter ballistics. Further, and most problematic, to accurately measure rumble the rumble in the test record must be significantly lower than the rumble in the turntable being measured. For best results, the test record should be a fresh lacquer master. A pressed test record will have more rumble than a lacquer master because of small irregularities in the plating used to make the stamper for the press. And the recording lathe must then have the lowest rumble of all. In real life, this isn’t the case. Good turntables, not just ours, have lower rumble than the lathe on which the test record was made and lower than the test records themselves, even masters. This is why it is difficult to get a number “that actually means anything.”

Nevertheless, we endeavored to determine what was possible and better understand the reality of these measurements and the protocols for making them. To that end we commissioned a test master cut specifically for us by a top mastering lab, with a meticulously maintained SP-10 direct drive lathe. In use, sadly, the only measurement possible was the noise in the groove of the test record itself. The cutting engineer confirmed that we were really only measuring the rumble in his lathe. It was impossible to test for noise in the turntable using this methodology. Because of this antiquated test standard and the higher standard of turntables versus cutting lathes, it was clear that when it comes to noise generation we would be forced to resort to non-standard methods to quantify and develop our design. We used internal listening devices and instrumentation to quantify any noise we might be producing and worked to eliminate it. Unfortunately, this means we cannot provide any useful data relative to our “rumble” when compared to the standard; it would only be speculation. We can only claim we are the quietest design yet and attempt to convince you with details about the design and fundamental education about the realities of noise in a design and how it may or may not manifest itself during usage. Our research showed that based on the fact that all records make far more noise than most turntables and that the noise from the table is well below the signal to noise ratio being generated, it becomes a theoretical problem, not one that actually manifests itself during usage. Most proper turntables have the noise issue adequately under control and will be well below the rumble level of a record. This may not be the case with the poorly made turntable. While our bearing is, in our opinion, the best possible design from a noise generation and isolation standpoint it is impossible for us, at this point, to prove this in any comparative way. Toward this end, we are continuing to work toward developing tests that will enable us to present a meaningful rumble specification that could be used to compare other turntables tested by the same method.

A similar but slightly more tractable problem is presented by wow and flutter. Surprisingly, there is little information available on the audibility threshold for flutter. The Audio Precision manual refers to 0.5% flutter as “unlistenable” (horribly bad), and we concur, but what about the other end of the scale? We set up some experiments to find out. In these laboratory tests, we generated flutter tones, and injected them directly from the generator into an Audio Precision flutter meter. We varied the amount of flutter modulation and listened carefully, noting the audibility of the flutter for different Peak Weighted Flutter readings, as shown below.

NAB IEC 386
0.5% = 0.7% is clearly audible.
0.2% = 0.28% is audible.
0.1% = 0.14% is audible, with effort.
0.05% = 0.07% is just barely audible if the flutter modulation is switched in and out.
0.02% = 0.028% is virtually inaudible.

Remember, these readings were made with flutter test tones, not music, so with solo piano, for example, the audibility number may be lower. Also, regardless of the number, any flutter in the playback turntable adds vectorially with the flutter contributed by the lathe, and/or analog master tape. More importantly, there are aspects of fine platter speed control for which there are no industry tests or specifications. By minimizing any playback time base instability, improvements in the realism of the acoustic soundstage are significant.

We had a problem measuring wow and flutter using test records because the recordings themselves are far from zero-wow/flutter specimens. But with wow and flutter we took an approach that was not possible with rumble measurements. We can measure the actual platter speed with extremely high precision using the platter’s optical encoder disk and a high speed digital counter/timer. By measuring the actual platter speed over segments of a revolution we can see any acceleration or deceleration, with ***100 nanosecond*** accuracy. Flutter and wow standards specify a sensitivity peak at 4 Hz. at 33-1/3 RPM, that's equivalent to about 45 degrees of platter rotation. For our tests we built a timing circuit that allowed us to look at four 45 degree segments, ¼ rev. apart (See Figure 2). Any variation in the time length of those 45 degree segments within a revolution shows the platter speed variation within a rotation (to the limit of the encoder disk accuracy). Using these methods we found the peak deviation from average speed to be typically 0.002% or less. This is an un-weighted indication of the error during a quarter revolution of the platter. Since a flutter measurement also indicates the peak platter speed deviation (expressed as a frequency delta) we can state that based on these measurements of actual platter speed, a Monaco Turntable has an un-weighted peak flutter of 0.002% or less. Not only is this an un-weighted result versus the weighted readings in our audibility tests, it's also about 20 times lower than the threshold of audibility revealed in those single-tone tests.

To summarize, if a given turntable has, say .005% RMS stated accuracy it could also be expected to have individual errors during playback as large as .007% from absolute. That would be 3.5 times less accurate than the Monaco Turntable. Our turntable, during a single-side playback period, will never have an error larger than .002% from the average speed.

Please Note: There are manufacturers that make misleading claims about speed control. When you read that a turntable has speed accuracy in the 5 parts per billion range, the truth of what is being said is that the crystal oscillator which is used as the clock for the speed control is accurate to 5 parts per billion. This has absolutely no direct correlation to the accuracy of the platter speed. Our system uses a similar crystal clock but we would never make such a misleading claim. In fact, these designs have no method of measuring actual platter speed and thus have no actual knowledge of what the platter may actually be doing. The crystal is used as a frequency/speed reference to adjust an AC or DC motor. The motor speed is the only thing that can be influenced by this device. With a belt drive system, while the crystal itself may be very accurate and therefore, perhaps, the motor speed, the introduction of a belt, a motor pulley, and platter with eccentricities and imperfect diameters destroy any hope of achieving true platter speed accuracy.

Of course the ultimate test for any turntable is the sound it produces. Upon completion of the first Monaco Turntable we immediately began an extensive series of listening tests and comparisons. These sonic evaluations were run concurrently with the on going and rigorous instrumented technical testing and development. Initially, this entailed comparison with a high quality contemporary belt drive turntable to determine if our prediction of sonic superiority due to the more precise speed control would actually be audible during playback. We were pleased to find that indeed the sonic superiority was immediately apparent, not only in pitch accuracy but also in superior dynamics, detail and soundstage presentation.

Included in the listening tests was the evaluation and selection of the thrust bearing materials. As was detailed earlier in this document the characteristics of the thrust pad as well as its interaction with the thrust ball will have an impact upon playback sonics. Thus we listened to nearly a dozen different materials before making a selection that meet our criteria.

Another key element of our listening tests was the tone arm evaluations. We evaluated a number of the more popular high end tone arms; Tri-Planar, DynaVector, Graham Phantom, Morch (both length tubes), SME 4.5i, and Wilson Benesch. In order to do a proper installation and then an evaluation of performance, we had to acquire one of each. After careful inspection and confirmation of the physical dimensions and mounting details for each tone arm, we designed and produced the required arm boards. We then set up and listened to each individual arm with at least two different cartridges (DynaVector XV-1s and Transfiguration Orpheus). What we learned was that the Monaco Turntable is fundamentally free of coloration and has proved to be an ideal platform for comparing and evaluating tone arms. We can design and produce arm boards for other tone arms as required by our clients.

Lastly, we tested the final product for EMF characteristics and worked to eliminate anything that might at any level manifest itself during playback. Even with the low 5 volt DC power used by our drive system, it did require some work to remove all spurious interference. We set up a turntable with a tone arm rigged to act as an antenna enabling us to detect any EMF that might affect playback (Note; for any tone arm installation, twisting the internal cable leads will go a long way to eliminating EMF. Our testing was done without twisted leads). After months of trial and error testing incorporating various types of magnetic shielding and several types of Ferrite materials we found a specific combination of treatments that eliminated any EMF contribution to playback.

Presented below, as transparently and as factually as possible, is data that proves why our design is the most sophisticated and accurate turntable available today. The graphical presentations are of data generated during the speed accuracy testing of our turntable. Also shown are photos of the digital oscilloscope screen during these tests. The caption for each figure will detail the information presented. Basically, this presentation shows the exact platter behavior while playing a record with the stylus in place. Any concern for speed error due to stylus load has been eliminated. The data below demonstrates, under real world conditions, the extraordinary speed accuracy and thus the frequency/pitch accuracy of the Monaco Turntable.

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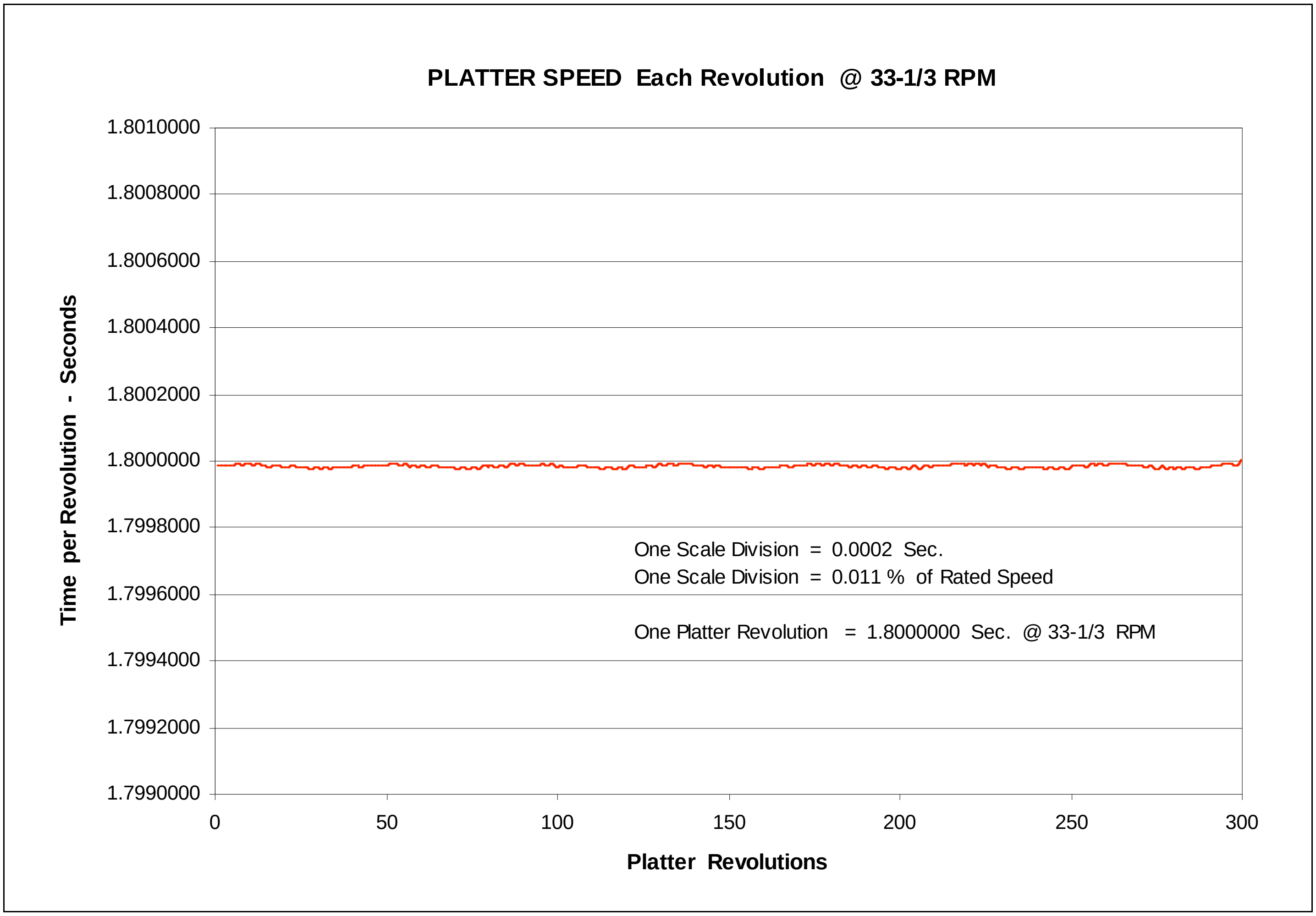

Figure 1 - Measured Platter Speed

This graph shows 300 separate measurements of the actual elapsed time for each platter revolution. The red trace shows the actual speed is very nearly perfect over 300 rotations. All measurements were within .002 % of the set point speed of 1.8000000 seconds per revolution (33 1/3 rpm).

Note: Spreadsheets showing all the original data comprising this and other graphs can be found on the Grand Prix Audio web site.

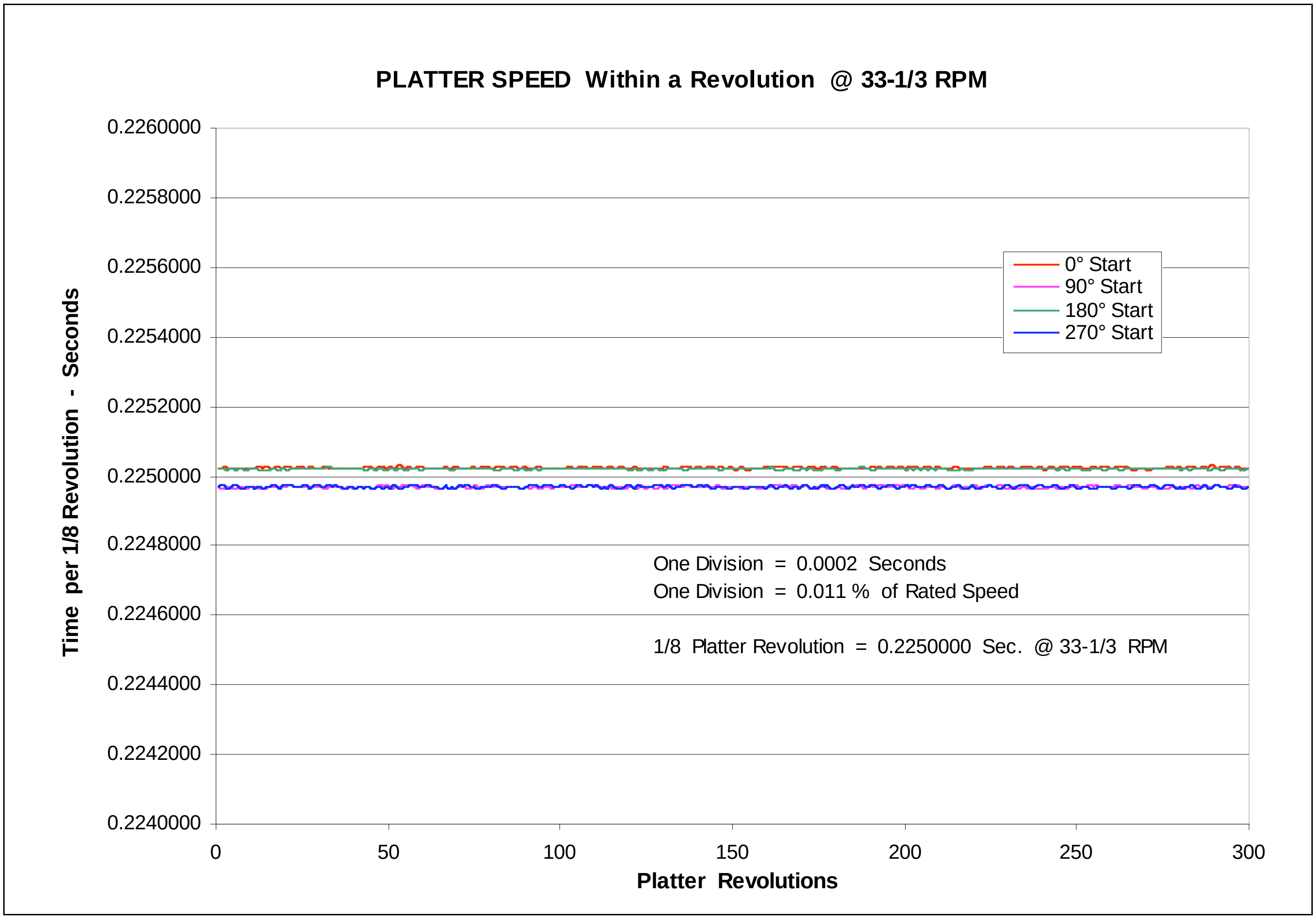

Figure 2 - Flutter Measurements

In attempting to measure short-term platter speed variations we've had to invent measurement techniques that didn't rely on the less than perfect test records. This test measures short-term (4Hz) speed differences by looking at a 45 degree segment of the platter rotation 4 times in each revolution. The graph shows small deviations from the mean speed, faster at two points 180 degrees apart (red & green traces), and slightly slower (magenta & blue traces) at two points 90 degrees advanced from the faster pair. Although this test method is much more sensitive than a flutter test utilizing a test record and flutter meter, the resolution is still limited to some extent by the technology available to make the measurements. The fundamental accuracy limit is tied to the capability of our test method rather than in the platter speed variations we're trying to measure. We're addressing this, and we've made progress with these tests, but we still aren't 100% satisfied with the current state of the art in flutter testing.

The small deviations seen in the lines on the graph reflect the extreme accuracy to which we are measuring the platter speed. These are small deviations at the 5th decimal point and less.

Platter Speed vs Time to 33-1/3 rpm

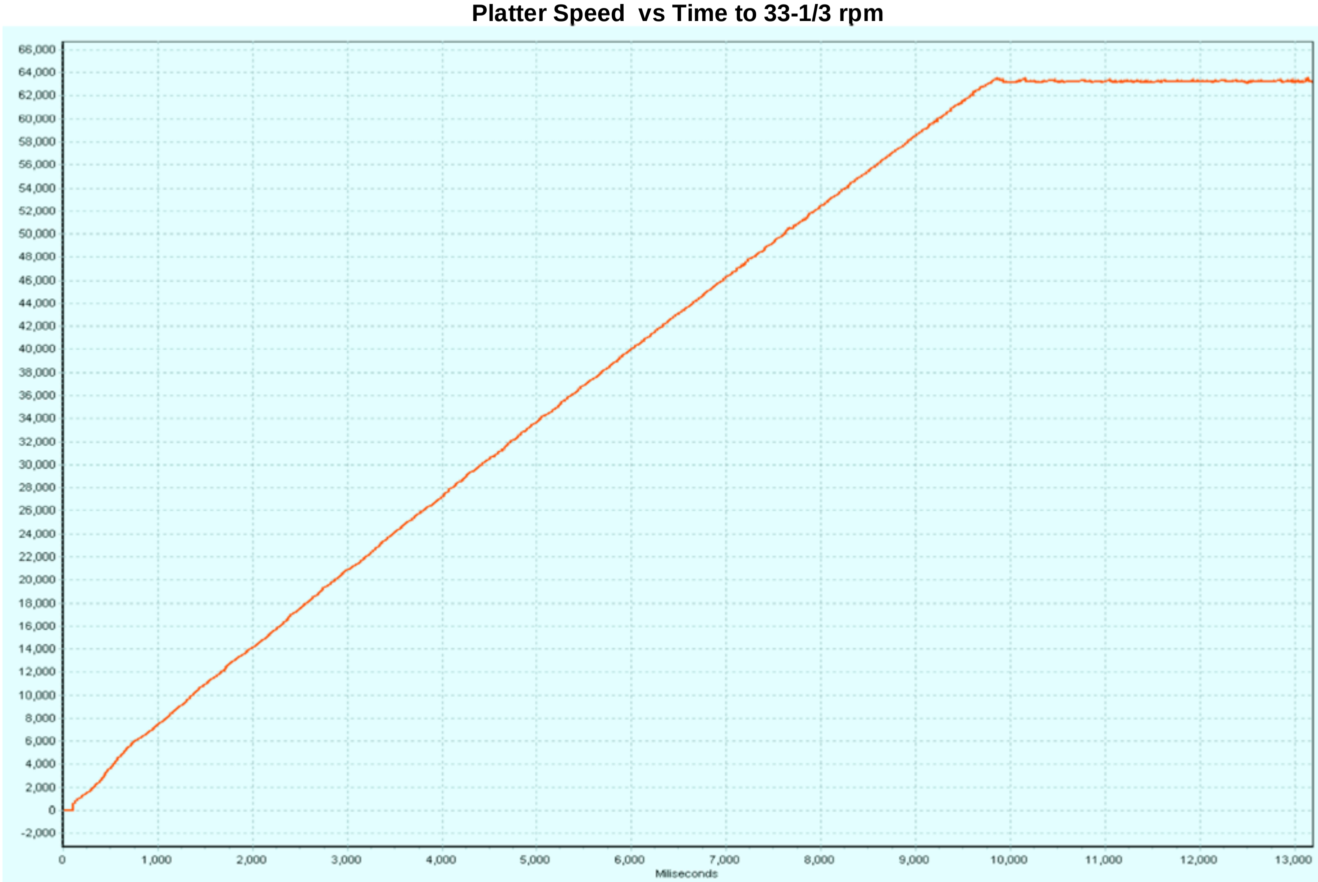

Figure 3 - Platter Speed during Start

This graph shows an extremely linear acceleration of the platter from a dead start to locked speed. The single overshoot at the corner is well damped and demonstrates a tight control of the platter speed. The typical run-up time to locked speed is around 10 seconds.

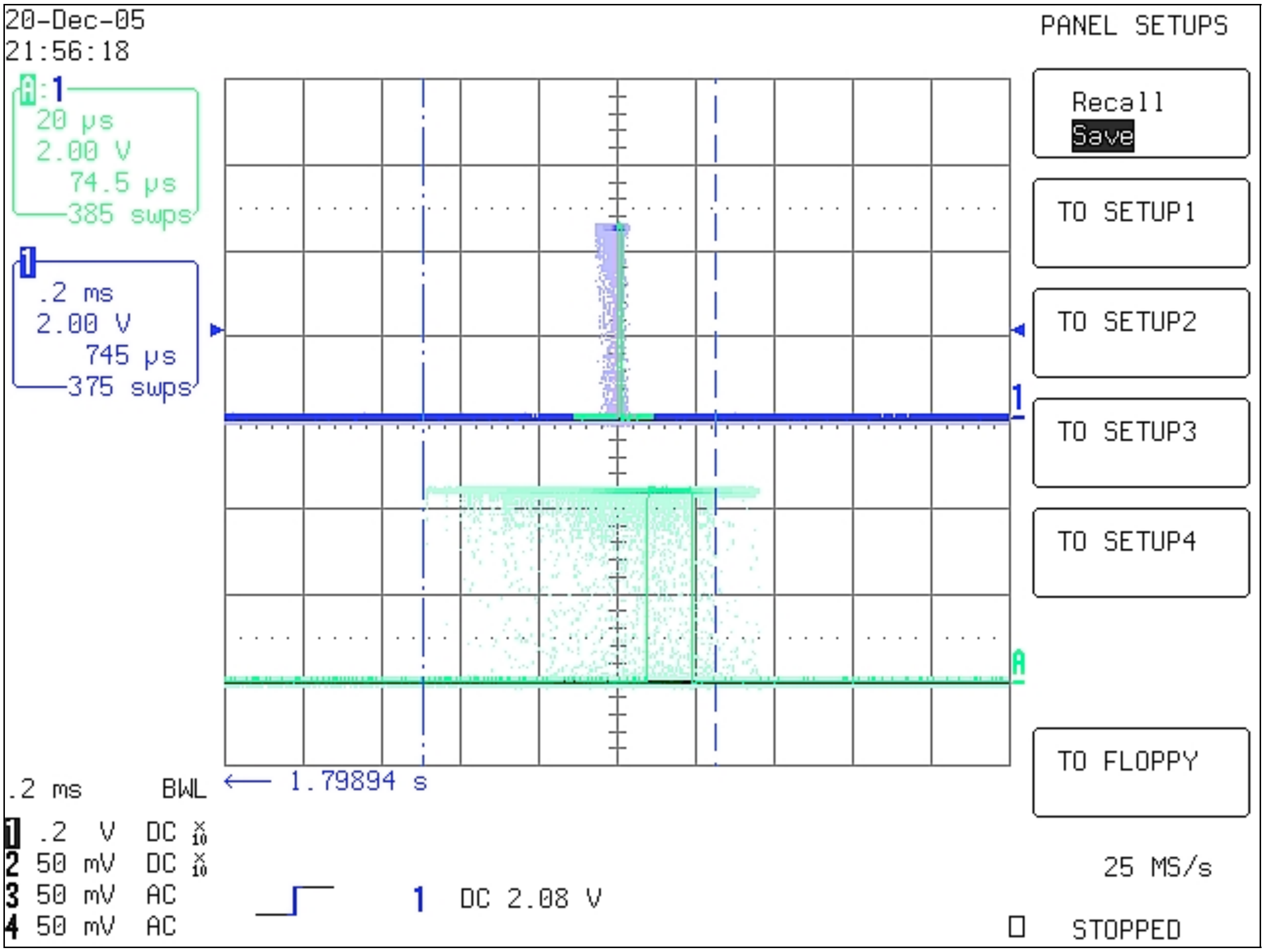

Figure 4 - Platter speed @ 33-1/3 rpm

This is a digital storage scope photo of a production Monaco turntable to verify speed performance. The test was made while a record was being played. The upper blue trace shows the index pulse from the platter's optical encoder disk. The green portion of the upper trace is magnified and shown as the lower trace. The trace builds up the histogram shown during 375 platter revolutions. The dashed vertical cursors show that the peak positional error of the platter falls within +/- 37.25 microseconds. This represents a 0.002% peak deviation from average speed in any rotation, over the 22.5 minutes of the measurement period. The measurement is made to 3-Sigma accuracy, which means a confidence level that the error in any given rotation will be less than the peak error 997 times out of 1,000.

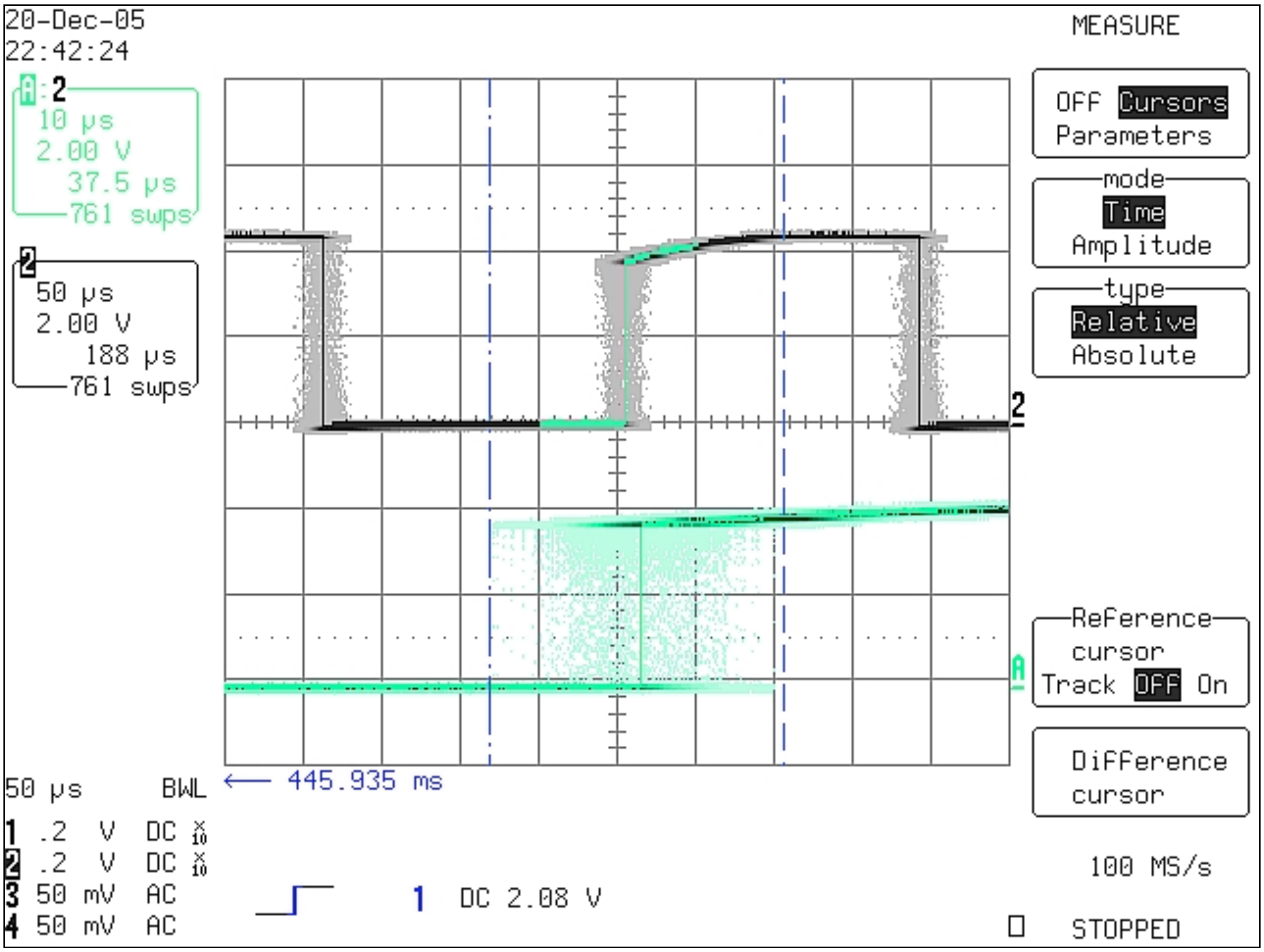

Figure 5 - Platter Speed @ 33-1/3 rpm in 90 degree segments

Similar to the above test, but the measurements were made on a quarter-revolution interval, rather than a full revolution, to see if variations occurred on a shorter time scale. The gray upper square wave is the encoder signal from the platter's approx. 4,800 line precision optical disk. The green rising edge of the waveform is the encoder edge located 1/4th revolution past the index pulse. It is magnified and displayed as the green lower trace. In this test the histogram shown represents 761 measurements taken over 1,522 platter rotations. The dashed vertical cursors show the worst-case positional error of the platter during a quarter revolution falling within +/- 18.75 microseconds, representing a **0.001% (10 parts per million)** peak deviation from average speed, over the 45.66 minutes of the measurement period.

Specifications

Speed Accuracy: Better than .002% peak deviation from average speed or a calculated .0014% RMS. This is based upon 3 sigma measurements. The speed error is never in excess of .002% at any time during this measurement process. This specification is, in fact, a conservative claim. We cannot measure wow & flutter error with a conventional test record and standard NAB methods or any other industry standard process; the turntable speed error is below the accuracy level of these tests. We do quote a peak % deviation from mean speed as we believe this better represents what you could hear.

Wow & Flutter: Below audibility: less than 0.002% or better. (See Tests and Measurements section)

Rumble: Our rumble performance is not measurable* using industry standard methods such as NAB, DIN, etc. Conventional rumble testing can only define the noise that exists in the standard test record since our design is far quieter than the original production process that produced that record. Noise generation by this design can effectively be considered to be irrelevant to playback performance. (See Tests and Measurements section)

Power Requirement: 9V DC, 1.5A Max.

Weight: 40 pounds

Shipping Weight: 75 pounds

* Using conventional industry standard tests such as NAB, DIN, IEC we cannot define the Rumble or Wow & Flutter of our turntable because the noise level and speed error of the record test groove is well in excess of the turntable itself.