The Combinative Application of Contact and Air Transducers On Selected Acoustical Instruments For Multi-Channel Recording

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In the quest for optimum timbral control in multi-channel recording, this paper investigates a method of sound pickup involving contact transducers along with air transducers. In this situation, a single contact pickup is able to reproduce excellent transient detail which can be electronically mixed with other transducer types, in order to provide the desired sound quality. Unlike air transducers which tend to integrate direct and reflected sound information, contact transducers respond to the immediate vibrational energy at a point source, and thus offer an intensified transient description of an instrument's timbre without the influence of the recording environment. The application of such devices, not only contributes to the timbral recognition of a sound, but may also be used as a simple yet effective method of signal processing, whereby the spectrum can be modified at the source. Spectral analysis of individual contact placements yields objective data which substantiates the subjective response to this method of pickup. An investigation of the acoustical correspondences between recorded timbres and vowel types provides the basis for a method of assessing the effectiveness of placement arrangements. The advantages of a combinative technique is explored in order to extend the repertoire of multi-microphone techniques.

A la recherche de la maîtrise optimale du timbre dans les enregistrements à voies multiples, le présent compte rendu étudie une méthode de prise de son où interviennent les transducteurs de contact ainsi que les transducteurs à air. Dans cette situation, un seul phonocapteur de contact peut reproduire d'une façon excellente des détails transitoires qu'on peut mélanger électroniquement à d'autres types de transducteurs pour obtenir la qualité de son désiré. Les transducteurs de contact diffèrent des transducteurs à air qui tendent à intégrer l'information sonore directe et réfléchie, en ce qu'ils réagissent à l'énergie de vibration immédiate à la source et qu'ils offrent ainsi une description transitoire intensifiée du timbre d'un instrument sans l'influence du milieu d'enregistrement. L'application de ces dispositifs ne contribue pas seulement à la reconnaissance du timbre d'un son, mais peut également servir de méthode simple et efficace de traitement du signal grâce à laquelle le spectre peut être modifié à la source. L'analyse spectrale du placement de différents contacts produit des données objectives qui démontrent la réaction subjective à cette méthode de prise de son. Une étude sur les correspondances accoustiques entre les timbres enregistrés et les types de voyelles apporte les fondements nécessaires à l'évaluation de l'efficacité du placement. Les avantages d'une technique combinée sont abordés dans le but d'étendre le répertoire des techniques à plusieurs microphones.

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A special thanks must go to my parents and my wife, Robin, for their support and love.

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(C O N T E N T S)

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CHAPTER 1

INTRODUCTION: MULTI-MICROPHONE TECHNIQUES

One of the most challenging yet unexplored areas of recording research deals with the acoustical and timbral analysis of multi-microphone placement techniques on acoustical instruments. Of the few published sources which are available, the studies by Woszczyk and Bartlett provide the clearest methodology with which to treat the subject.[1] The former author bases his work on the hypothesis that an instrument's recorded tonal features may vary depending on the acoustical characteristics of the recording environment and on the microphone arrangement utilized.[2] After an acoustical analysis of the important direct and reverberant energy fields, Woszczyk successfully demonstrates an effective and natural means of timbral shaping by close multi-microphone setups.

> «Natural equalization of a sound spectrum can be accomplished by employing several microphones to independently pick up characteristic spectral qualities of the instrument, enabling the engineer to combine in desired proportions the various spectra produced by the source. This method also provides possibilities for composing new balances with natural ingredients and other creative manipulations.»[3]

In order to expand the repertoire of effective multi-microphone techniques currently in practice, the focus of this study is on the theoretical and practical application of a combinative microphone placement technique which uses contact pickups (piezoelectric transducers) and air transducers.

In the second chapter, calibration of typical pickups is carried out and the data is compared with a high quality professional piezoelectric transducer. It is safe to assume from this preliminary investigation that many audio pickups suffer from manufacturing improprieties which often result in inconsistent voltage sensitivity ratings and in an uneven frequency response. Discussion is based on the more significant electroacoustical parameters including the importance of proper mounting procedures. Graphs demonstrate the variance in frequency response due to mounting changes.

Without a proper understanding of the acoustical nature of instrument design, the application of contact pickups on the multi-resonant body of a stringed instrument often proves hazardous. Due to its extreme proximity to the vibrating body, a contact pickup is much more sensitive to local resonant energies than other transducer types. Most sound engineers are aware of the fact that even a slight movement in the pickup position can elicit major timbral changes.

The third chapter opens with an investigation of some of the more problematic aspects of instrumental acoustics as they apply to the use of contact pickups. For example, a discussion on the function of the main resonances and the acoustical importance of the physical structures (i.e., bridge, sound post, etc.) of stringed instruments, serves to guide the engineer towards proper contact application.

Chapter four is meant to provide a simple, yet objective method by which the tonal effects of placement techniques (conducted later on in this study) may be evaluated. In essence, this method is based on the categorization of recorded timbres in terms of acoustically related vowel types. For example, a frequency analysis of a placement will disclose a spectral envelope which corresponds with the formant shape of a particular vowel. Thus the placement is given a vowel-identity. Discussion of acoustically based descriptive terminologies helps to further characterize the recorded timbre.

Chapter five investigates the tonal effects of individual contact pick-ups on a number of acoustical instruments. In this section, analysis is conducted in the frequency and time domains, by means of a high-speed digital spectrum analyser. Each placement is given a vowel-identity in order that tonal differentiations may be clearer. Data is provided which indicates the objective and subjective correspondences existing between recorded timbre and vowel colour.

The final chapter utilizes the spectral data previously obtained in order to demonstrate the tonal effectiveness of a combinative microphone technique. Graphs compare the distinct spectral contributions produced by the contact and by the more distantly placed air transducers. Suggestions are then made for combinative arrangements which feature defined timbral characteristics.

CHAPTER 2

CONTACT PICKUP CHARACTERISTICS: THE NEED FOR CALIBRATION

The absence of objective data on audio pickups present an obstacle to the understanding of its proper application. In fact, to this author's knowledge no manufacturer of piezoelectric accelerometers, (which are to be used in professional audio situations), supplies calibration information regarding their product. Instead, manufacturers are likely to emphasize placement strategies while foregoing product calibration. However, without any clear,objective proof regarding product performance, the engineer not only may question whether the pickup itself is causing major spectral changes in the sound, but, at the same time, he can never depend upon the consistency of the pickup, even when they are produced by the same manufacturer.

The main reason for this unfortunate state of affairs is a result of economic reality. A calibration chart for each transducer would likely double the cost of the pickup and thus discourage many potential customers. Furthermore, calibration information is oriented for precision testing, and would be too technical in nature for the typical audio user. Besides, even very sensitive individuals can tolerate far greater distortions and unlinearities in the signal than could be accepted in more critical reference work, where, for example, an extremely wide and flat frequency response is required.

The solution, it would seem, is in the nature of a compromise. Contact pickups, to be used in professional and semi-professional audio applications should follow the way of other high-quality air transducers which provide some basic information concerning sensitivity, frequency response, and dynamic range. In all likelihood a rise in cost of the device would be compensated by an increased trust of the product especially in professional circles.

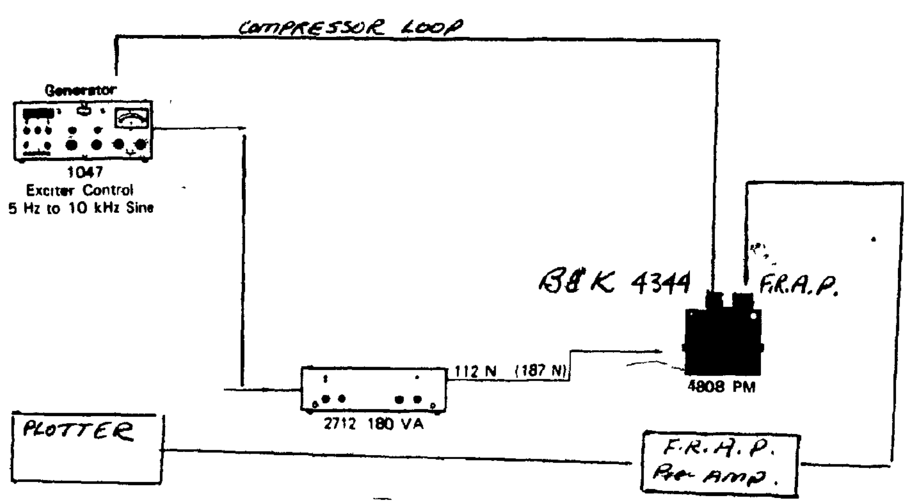
In this chapter, attention is placed on the theoretical and practical aspects of contact pickup design. Two of the pickups used in the placement experiments (Chapter 6) are calibrated and then compared with a B & K reference accelerometer model 4344. Although the results from this investigation do not intend to be conclusive, the data does draw attention to some of the limitations of the product with respect to the sensitivity and the reliability of this device when utilized in a practical recording situation.

CONTACT PICKUP DESIGN

In professional audio applications, the term «contact pickup» generally refers to a type of transducer which responds to the acceleration of a vibration at a specific point in the instrument's body.[1] The active element in this kind of transducer consists of a number of piezoelectric discs which can generate (over the required dynamic and frequency range) an electrical charge proportional to the applied vibration.[2] In the experiments conducted later on in this study, the pickup is of a tri-axial design whereby the accelerometers are designed orthogonically (i.e., in three mutually perpendicular directions). The resultant output then consisted of a single vector-summed output.[3]

METHOD OF CALIBRATION

In order to compare the sensitivity of the F.R.A.P. pickups with the high-quality B & K 4344 accelerometer, both transducers were mounted as close together as possible on the table of a vibration generator (B & K model 4808). A signal generator (B & K model 1047) provided a frequency sweep between 5Hz. to 10Hz. A compressor loop from the reference accelerometer to the vibration generator was used to keep the acceleration of the load constant for the required frequency range. Powering of the excitor was done by a B & K power amplifer model 2712. Each F.R.A.P. under examination, used the same pre-amp supplied by the manufacturer. The following diagram illustrates the calibration setup utilized.



RESULTS: SENSITIVITY

Sensitivity rating of a piezoelectric accelerometer is determined by the ratio of electrical output to the acceleration of the vibration under study.[4] In high-quality accelerometers the voltage sensitivity (specified in mV/mS^{-2} or mV/g) includes the capacitance of the cable supplied and is determined at room temperature (20°C) at a frequency of 50 or 160Hz. A high-quality reference accelerometer like the B & K model 4370 for example, has a voltage sensitivity of 7.43 mV/mS^{-2}.

Not only did measurement values of the sensitivity for the two F.R.A.P. pickups vary noticably from the reference but also from each other. The values obtained were 4.3mV/mS^{-2} and 1.8V/mS^{-2} for each pickup at 1.0KHz. This inconsistency can affect timbral definition especially in low energy vibration situations.

FREQUENCY RESPONSE

The upper frequency limit of an accelerometer is primarily dependent upon its mounted resonance frequency and by the amount of damping supplied from the pickup itself.[5] Since the damping factor is usually quite low, the main problem affecting high-end response appears to be in the mounting of the pickup. A less than rigid or flush mounting of the pickup can substantially lower the mounted resonant frequency and thereby limit the upper frequency boundary of the operating range.

On the other side of the spectrum, low-frequency limitations are generally set by the pre-amplifier. Audio requirements are easily met in the amplitude changes in the lowest end (around the 20-40 Hz. area) are quite small.[6]

Graph I illustrates the frequency response of a B & K 4344 accelerometer, which produces a relatively flat response from the 10Hz.-10KHz. (less than a 6% or 0.5dB error). This may be compared to Graph II, which illustrates the frequency response of the first pickup tested. In this case, one notices a trough between 40-80Hz., with a smaller one at 7.0KHz., while a peak occurs at 5.0KHz. A slight change in the mounting position of this pickup produced significant alterations of the frequency response, especially in the lower end, (demonstrated in Graph III). The trough here is deeper and is situated at 37Hz. The high-end response between 5-10KHz. is very similar to the previous placement.

Significant variations in the frequency response were encountered with each remount. Graphs IV, V & VI illustrate the changing response of this pickup with reach remount. Overall, the most drastic variations can be found between 20-80Hz. In general, both pickups displayed a more linear output for the 400-3.0KHz. area. Slight emphasis around 5KHz. is also a shared feature for the two transducers.

One can conclude that these particular pickups will provide a more linear output in the mid-to-high frequency areas (i.e. up to 10KHz.), even with different mounting positions. On the other hand, low-end response varied greatly below 80Hz. and was thus more sensitive to changes in the mounting setup.

GRAPH I

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Sign: ______ Recording Mode ______ Zero Level: ______ Potentiometer Range ______ dB Wr. Speed ______ mm/s

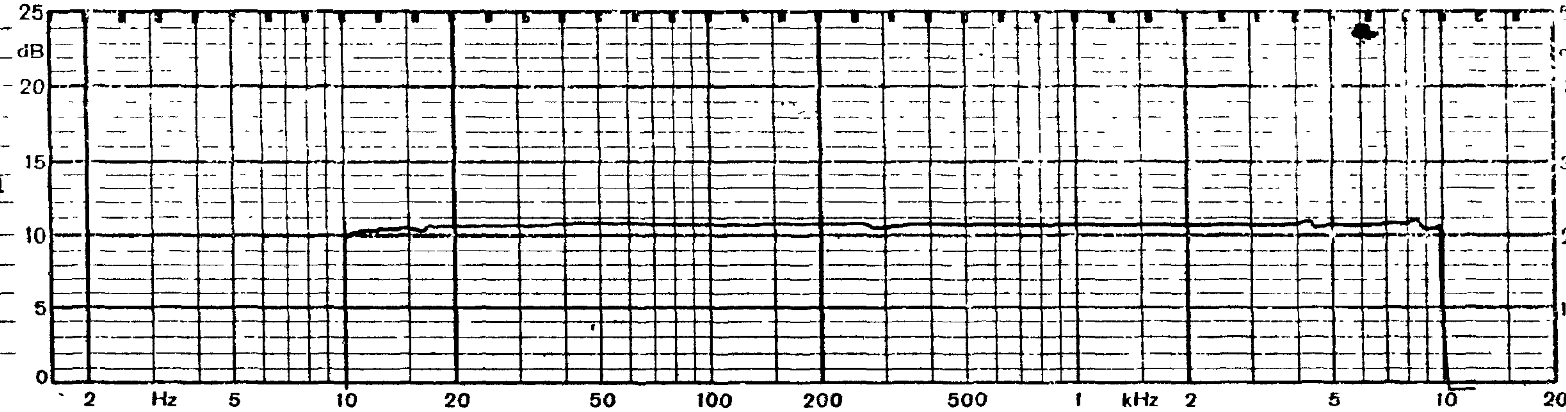
Measuring Object ______

B & K
Model 4344

Y 2 Scale ______

Channel 2

QP 2120



GRAPH II

Sign: ______ Recording Mode ______ Zero Level ______ Potentiometer Range ______ dB Wr Speed ______ mm/s

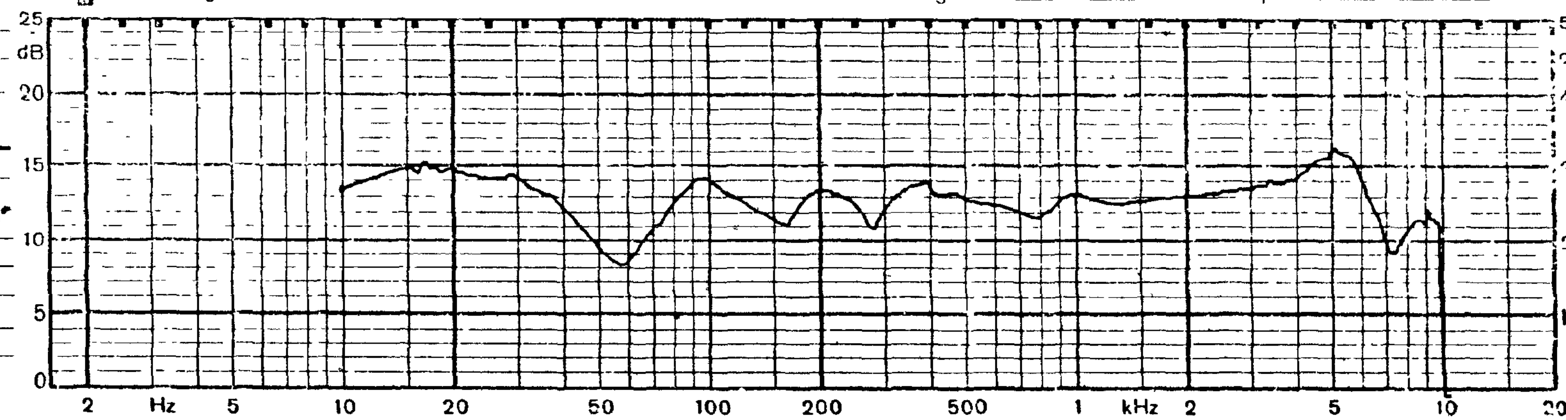
Measuring Object ______

F.R.A.P. #1
4.3mV 1KHz.

Y 2 Scale ______

Channel 2

QP 2120



GRAPH III

Sign:

Recording Mode: Zero Level: Potentiometer Range: dB Wr Speed: mm/s

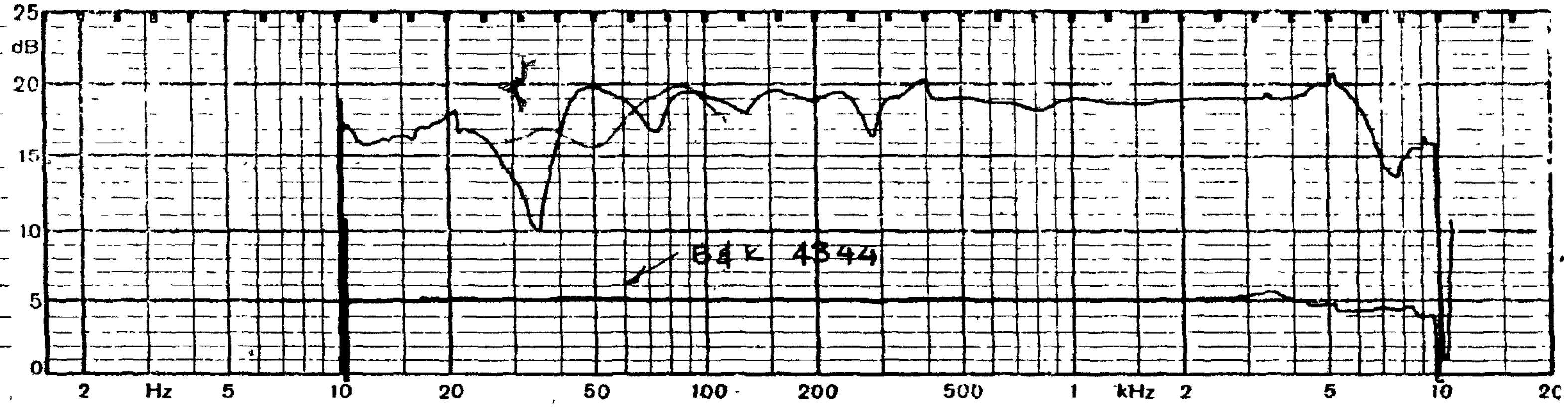
Measuring Object:

F.R.A.P. #1
Remainted

Y 2 Scale

Channel 2

QP 2120



GRAPH IV

Sign:

Recording Mode: Zero Level: Potentiometer Range: dB Wr Speed: mm/s

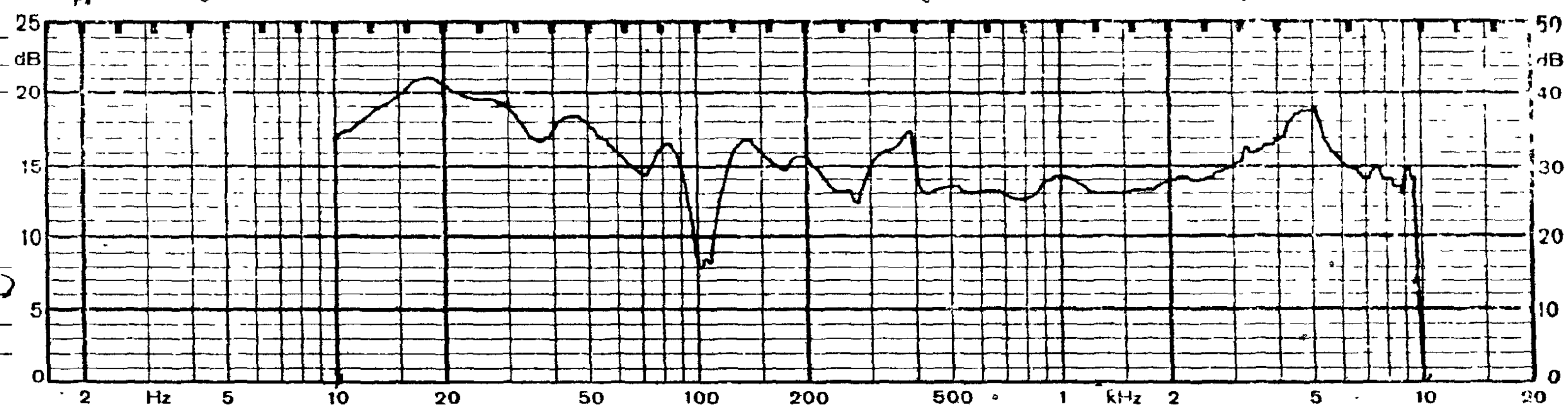
Measuring Object:

F.R.A.P. #2
1.8mV 1KHz

Y 2 Scale
(same preamp)

Channel 2

QP 2120



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GRAPH V

Sign: ______ Recording Mode: ______ Zero Level: ______ Potentiometer Range ______ dB Wr. Speed ______ mm/s

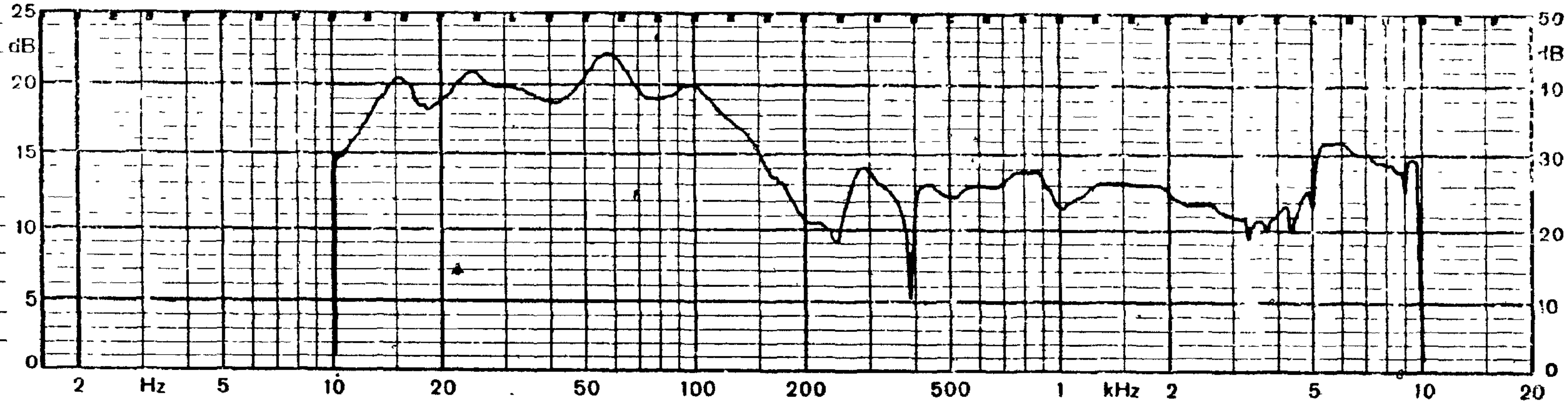
Measuring Object ______

F.R.A.P. #2
REMOUNT

Y 2 Scale: ______

Channel 2

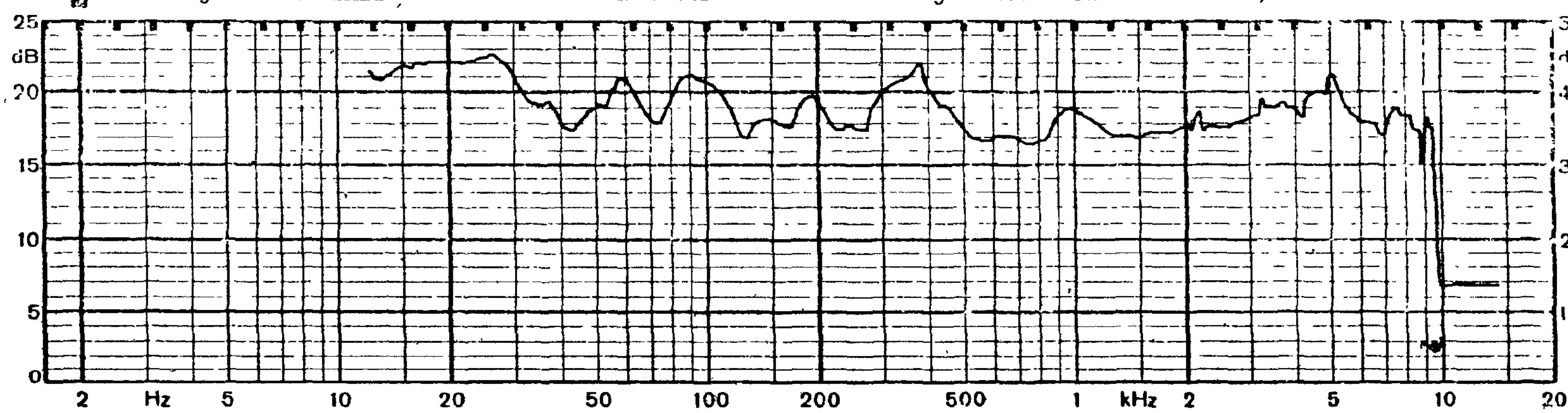
QP 2120



GRAPH VI

Recording Mode ______ Zero Level: ______ Potentiometer Range ______ dB Wr Speed: ______ mm/s

#2
REMOUNT



PHASE RESPONSE

The relationship between an accelerometer's sensitivity and phase response is such that at frequencies below the natural resonance, the time or phase shift introduced is usually small.[7] However, phase distortion increases as the mounted resonant frequency is approached, causing variable delay patterns across the audio band width. With high quality accelerometers, phase distortion is minimized by narrowing the mounted frequency resonance through damping and by ensuring phase linearity in the voltage preamplifier.[8] Although testing in this parameter could not be done, there is evidence that a properly designed phase-linear contact/preamplifier system can be more effective than air transducers in reducing timbral colorations caused by phase distortion. In addition, pickups are not subject to acoustical phase interferences which may hamper signal fidelity in air transducers.

DYNAMIC RANGE

Since the output of an accelerometer is theoretically linear over the required frequency range, the dynamic range is governed by the overall noise level of the system.[9] In this case, the lower limit is established by the noise output of the preamplifier. Short cables which are rigidly secured to the accelerometer provide the least amount of noise. In preamplifiers powered by batteries, there is a risk of greatly increasing the noise factor due to the weakening of the battery. (In the pickups under examination the reduction of the signal-to-noise ratio was a result of battery run-down. Because of this, it appears that an important performance characteristic, which should be established, is a weighted signal-to-noise ratio of the entire system. Although strict measurements were not made, the signal-to-noise ratio of the pickups under investigation were perceived to be between 50-60 dB, which may not be sufficient, considering the large differences in body vibrations throughout the surface of the instrument.

TRANSIENT RESPONSE

Since instrumental vibrations produced are transient in nature, care must be maintained to reduce waveform distortion occuring at the onset of the life of a tone. Transient distortion is primarily caused by low frequency phase non-linearities of the preamplifier's integration network, and by the high-frequency ringing effect generated by the accelerometer itself.[10]

In typical audio pre-amplifiers, the low end is less problematic due to advanced electronics. In order to avoid the 'ringing' effect, the resonant frequency of the pickup must be far above the required range, or else, some form of high-frequency attenuation should be incorporated.[11] In experiments found later on in this paper, 'ringing' effects were maximum for the piano and the violin.

MOUNTING

Perhaps the single most important factor which can influence the frequency response of the accelerometer, is the manner in which the pickup has been mounted. As shown before, when the contact is less than rigid or flush, there is not only a change in the higher end but significant amplitude alterations in the low to mid frequency range. While the use of bees wax may not offer optimum performance in all situations, it will insure a relatively even frequency response due to its stiffness.[12]

CHAPTER 3

ACOUSTICAL CONSIDERATIONS FOR THE APPLICATION OF CONTACT PICKUPS

INTRODUCTION: MULTI-RESONANT SYSTEMS

The distinctive timbral signature of an acoustical instrument is shaped by the multi-resonances produced by the vibrating body.[1] The frequency response of a contact pickup moved from one point to another along the instrument's surface, reveals general alterations or modifications in the spectrum. In order to take advantage of the multi-timbral capabilities inherent in the changing acoustical radiation patterns, a single contact pickup may be disposed at strategic positions. Several contacts, each providing a well-defined tonal identity can be combined through multi-channel recording. In this manner recorded timbres are totally composed or assembled from the source and do not rely on electronic equalization.

The arrangement strategy utilized in this study is based on the premise that unique timbral colorations occupy specific locations on the sound board. The highly selective pickup response of the contact allows direct access to localized tonal colorations. This type of pickup selectivity is not possible with air transducers tending to integrate both direct and reverberant information.

In the following, a discussion centers around the acoustical significance of the various physical elements (i.e., plates, bridge, sound post, etc.) affecting an instrument's timbre.

THE PLATES

The resonant characteristics of the body has long been a subject of great interest for instrument makers. Investigations of the vibrational modes of the top and back plates of a violin have been carried out since the time of Savart (1840) and Helmholtz (1863)[2]. More recent studies by Hutchins, Saunders, Meinel, and Jansson[3] are responsible for the development of an objective method for examining the frequency response of the top and back plates. Such data helps the recording engineer select potentially useful placement areas.

Hutchin's study of the resonance structure of a violin came to the conclusion that the violin has between 30-40 resonances.[4] The tonal quality of a recorded sound is largely determined by the proximity of the pickup to one of these resonances. The closer the transducer is to a resonance center, the greater the energy exchange from the local resonant area to the pickup. A contact pickup may be able to follow the fine, transient detail of the waveform more accurately than can an air transducer.

Of the multitude of resonances inherent in the body, there are three which provide the greatest influence on the reproduced timbre. The first is the low-frequency resonance of the body, designed to provide support for pitches around the second string. Hutchins found that this so-called main wood resonance combined with a subharmonic wood prime resonance (one octave below the main wood resonance) helps strengthen the lowest resister.[5]

Occasionally, the interaction between the main wood resonance and the vibrating string result in the bothersome wolf tone. In this case, when the body is excited by the strings at the frequency of its main wood resonance the sound may quaver and break up an octave. The reason is that energy is quickly exchanged between the string and body.[6] The shuttling of energy has the effect of thinning the sound and is especially noticeable with contact pickups.

A third major resonance is formed by the first vibrating mode of the trapped air inside the body and is commonly called the main air resonance.[7] This resonance is shaped by the volume of air in the body and by the «f» holes. The interaction of the plates and holes from what is generally called a Helmholtz Resonator. Its function is to give support to the register around the third string.

Saunders devised a method of analysis to determine the importance of these resonaces on the quality of violins.[8] A set of loudness curves showed the changes in amplitude with frequency. For good-quality instruments, a distance of a perfect fifth was found between the main air resonance and main wood resonance,while poor ones displayed a large frequency differential between plates. Moreover, it was found that fine instruments demonstrate an even spacing between the wood prime, main wood, and main air resonances.[9]

However, such a symmetrical arrangement of resonant peaks is not found on the lower bowed-string members. For the viola and cello, Hutchins determined that the main resonaces fall several semitones above the middle strings, and are thus less helpful in amplifying the lowest register.[10] Such irregularity in design is explained by the fact that the optimum size needed to lower these resonances would impose a tremendous obstacle to the performer. Because of their smaller dimensions and subsequent higher body and air resonances, there is some difficulty in low-frequency radiation.

I.P. Beldie examined the vibrational patterns of good-quality violins.[11] In these experiments, fine particles of sand were spread over one of the plates, while an audio frequency generator set the plate into motion. The results illustrate that between 120Hz.-600Hz. the back plate contains two or three main resonances while the top plate is more active. An instrument whose top-plate peaks were evenly spaced with those of the back plate was considered to have a superior tone.[12]

More recently, sophisticated research involving hologram interferometry measurements of the resonance-vibration motions of the top plate of a violin have been performed by E. Jansson.[13] Essentially, this technique provides photographs of the amplitude distribution for various frequencies over the surface of the plate. Jansson concluded that: a) the main top plate resonance is radiated towards the lower left side; b) a maximum vibration amplitude occurs as one draws nearer to the «f» hole; c) a null point exists at the sound post; d) at lower frequencies the violin vibrates as a simple source (or as a unit) as frequency increases doublet vibration patterns exist; 3) the middle or waist of the violin tends to divide the vibrations into two areas (i.e., one near the neck and one near the bridge).

General placement guidelines can be concluded from these studies. For example, rigid or less flexible areas found on the back plate and sides are less likely to receive high-frequency information and thus one finds timbres with muted high-frequency components. On the other hand, thinner and, therefore, more pliable areas surrounding the «f» holes enjoy greater vibrational activity, consequently generating stronger high-harmonic components. In this case, the recorded timbre is «brighter».

THE SOUNDPOST

The effect of the soundpost on the reproduced sound was examined by Savart (1840)[14]. He compared a violin that had a soundpost with one that did not and concluded that in the latter both the main-wood and main-air resonances were higher. Later work by Schelling showed that by introducing assymetry, the soundpost reduces the cancelling motion between plates.[15]

It is significant that while the soundpost provides especially good mechanical coupling for low frequencies, at higher frequencies the post is generally slightly less effective. Thus the area directly surrounding the post on the back plate will exhibit a more-balanced frequency response than other points on this plate. A contact positioned at this location will tend to reproduce a fairly «rounded» and «full» tone.

THE BASS BAR

The bass bar runs lengthwise under the lowest string, along the top plate. Hutchins states that its main function is to distribute the load of the bridge over a larger area of the top plate, helping the body withstand the downward force of the string tension.[16] Situated near the left foot of the bridge, the bass bar transmits the bridge vibrations to the rest of the top-plate surface.

THE BRIDGE

The function of the bridge has been studied by Minnaert, Vlanland Bladier (1960), Hutchison (1962)[17]. It was found that as the bow is pulled across the strings, a force is exerted on the bridge creating a see-saw motion upon its legs. In point of fact, the bridge is set into three basic types of motion; a) perpendicular to the belly; b) along the belly; c) perpendicular to the plane of the bridge. Of the three, the greatest vibrating motion is to be found for the first.[18]

The vibrating motion of the bridge is a function of frequency. In the lowest range (20Hz.-200Hz.), the left foot is most active, assuring good low-frequency radiation into the body (and thus to the back of the instrument). Bladier surmised that the bridge of a cello acts as an amplifier with an acoustical power rating of 2 (6 dB.) for the range 66Hz.-600Hz. He found that the bridge radiates higher frequencies with less power.[19]

SPECTRAL CHARACTERISTICS OF STRINGED INSTRUMENTS

THE VIOLIN

Saunders (1937), Meinel (1957), Yankovskii (1966), Olson (1967), and Meyer (1976)[20] have contributed to the understanding of the frequency response of stringed instruments. In most cases, the objective spectral data was correlated with subjective descriptions of quality. The conclusions drawn from these studies serve to direct the audio engineer towards a more objective approach in microphone techniques.

In his earliest experiments, Saunders analysed the frequency response of a Stradivarius Violin. He found five major peaks of which the first two are the main air and wood resonances respectively. The third occupies a space a major sixth above the main-wood resonance. The fourth is an octave higher, while the fifth is found to be a minor seventh above the fourth. Beyond this, he observed that a persistently strong area exists from 1.7KHz.-2.2KHz. In addition, he concluded that the lowest string produces a weak fundamental, while the second and third harmonics are strongest.[21]

Meinel confirmed Saunders' view that the«full»or«sonorous»quality of good violins can be directly correlated with large-amplitude levels for the lowest harmonics.[22] In his study, he found that when a single, large peak occurs at 1.5KHz., a «nasal» quality is perceived, while a large amplitude in the 2.0KHz.-3.0KHz. range adds «presence» to the sound.[23]

Olson compared the acoustic spectrums of the open strings of a violin.[24] He discovered that the «G» string exhibits a weak fundamental while having a strong region from the second to sixth harmonics. The «D» string, supported by the main-air resonance, has a strong fundamental and third harmonic. The «A» strong shows a strong fundamental, but weak second to fourth harmonics. This string also displays strong higher partials. Finally, the «E» string has a fairly strong fundamental, third and eighth harmonic components.

Yankovskii correlated his objective spectral analysis of the violin with subjective interpretations, in order to devise a reliable system for the evaluation of tone quality.[25] After analysing the spectra of many types of violins, Yankovskii determined that a good instrument has a dome shaped frequency envelope with a maximum at 1.25KHz. In addition, he found strong peaks at 250,500, 800Hz. (with the 500Hz. component slightly greater than the 800Hz. peak). If too deep a trough exists between 500-800Hz., then the tone is found to be «hollow».

Violins with a strong region from 2.5KHz.-4.0KHz. were described as «bright» with a «strident», «trebly» sound, signifying a deficient radiation below 500Hz. A «thin» or «tight» sound forms a plateau-shaped envelope beginning at 500Hz. and extends to 6.3KHz., with little low or high-frequency information. A «piercing» timbre correlates with a spectral maxima of 4.0KHz. «Nasal» tones exhibit a sharp peak between 1.6Kz.-2.0KHz. From this study, Yankovskii concludes that it is possible to classify violin timbre according to the distribution of energy within four prescribed frequency zones, i.e., below 200Hz.; 200Hz.-900Hz.; 2.2KHz.-4.5KHz.; and above 4.5KHz.[26]

In this simple, yet effective manner, Yankovskii defines the major frequency boundaries within which timbral characterization takes place. Moreover, his study draws together objective data based on frequency analysis with descriptive verbal terms. Words such as «bright», «noble», «soft», «piercing», «harsh», «tight», as well as ones associated more with music per se, provide a suitable means for subjective interpretation. Likewise, at a later point in this study, an attempt to verbally classify recorded timbres using phonetically based terms will be rendered.

Meyer investigated the frequency and transient response of the string family in order to find the salient acoustical features.[27] Like Yankovskii and Helmholtz before him, Meyer utilizes verbal terms to delineate tonal qualities. In addition, his study links vowel formant structure with musical timbre.

For example, Meyer states that the typical formant found for low notes of the violin occurs at 400Hz. This resonance supports the lower register of the instrument and contributes to the dark, back-vowel quality /o/. A second formant around 800-1.2KHz. is responsible for a «nasal» quality. Although Meyer is reluctant to identify consistent formant patterns for most instruments, he does mention the response of an extremely fine Stradivarius «Prince Khevenhulle» that produces a consistent formant structure for forty of the fifty-two notes tested.[28]

However, the full characterization of musical timbre cannot be realized by an analysis of the frequency envelope alone. In addition, each instrument also possesses individual temporal features which aid in the recognition of timbral types.[29] In effect, the most significant aspects of the time-varying waveshapes produced by acoustical instruments are: transient duration (i.e., the time taken for the sound-pressure level to drop 3dB below the steady-state level); harmonic overshoot, and; harmonic instability.[30]

For example, in the time-domain analysis of placements conducted later on in this study, the violin yielded fairly long attack times for the lowest harmonics, while showing considerable harmonic instability for the highest harmonics. Generally, if an overshoot occurs during the attack, the particular harmonic(s) involved significantly colour the sound.

Therefore, one can conclude that the application of contact pickups can emphasize the unique temporal signature inherent in the waveshape due to its proximity to the vibrational source. In this manner, timbres are more clearly articulated and localized, thus improving tonal characterization.

THE VIOLA

Meyer found that the lowest register of the viola exhibited an intensity maxima around 220-250Hz.[31] The quality is comparable to the dark back-vowel /u/ sound. Other formant areas are located at 600Hz. and 1.6KHz. The first one contributes to the full mid-range quality associated with the middle vowel / æ / , while the second displays a more «strident», «nasal» characteristic. In addition, a peak centered around 3.0-3.5KHz. tends to diminish the «nasal» quality and offers greater «presence».

Transient duration times are similar to those of the violin. Tones played softly need slightly longer time to develope a full sound.[32]

THE CELLO

The main formant areas of the cello lie at 250Hz. at ranges between 300-500Hz., and 600-900Hz. The first formant supplies a dark back-vowel /u/ character to the lowest register. The cello may take on a brighter, mid-vowel color, contingent upon the position and the strength of the second and third formants. A pronounced peak at 1.5KHz. produces a nasal quality, while a secondary peak around 2.5KHz. contributes to the cello's trebly tone.[33]

The cello requires a much longer time (than the violin or viola) for its harmonics to develope, especially, in fast passages where the cello exhibits a hollow quality due to the inadequate time for the buildup of the transients to take place. One can expect transient durations of over 350mSec. for low notes.

THE BASS

The double bass exhibits two main formant areas. The first, occurs between 70-250Hz., and is responsible for the support of the lowest register. A smaller second formant is found around 400Hz. Occasionally, one finds a higher peak around 800Hz. A lengthy transient duration, in excess of 350mSec., is found for the lowest register.[34]

THE PIANO

Generally recognized as the most mechanically complex instrument in use today, the grand piano action utilizes thirty-five separate parts in order to produce a single tone.[35] However, the most significant contribution to the tonal quality is produced by the soundboard.

Unlike the bowed-string group, the piano soundboard is a single wooden structure. Olson explains that the large dimension of this sound radiator provides a significant, acoustical, radiation resistance.[36] This factor permits good, low-frequency reproduction.

Olson, Meyer and R.D. Weyer[37] examined the frequency and temporal attributes of piano timbre. Olson found that the tonal quality was a function of the intensity.[38] For example, when a player exerts a great force upon a key, an increased number of harmonics will be generated. Subjectively, the sound is described as «full» or «rich». However, due to the absence of harmonics for the highest register, an increase in intensity emphasizes a «trebly» or «strident» quality.

Meyer examined the spectrum of a grand piano and found that the fundamental is usually strong, except in the lowest two octaves where the upper harmonics dominate.[39] A strong formant area exists between 500-2.0KHz. In the highest register, harmonics are generated around 10KHz.

Both Meyer and J. Backus[40] have investigated the effects of string inharmonicity on piano tone. The gradual sharpening of the higher partials creates a roughness in the treble register. The departure from a purely harmonic relationship seems to be more critical to the quality of the bass register, where the fundamental is naturally weak. In this case, inharmonicity is responsible for an «ill-defined» bass.

Investigation of the piano tone in the temporal domain is rare. Weyer's studies show that the piano produces a waveform characterized by a pseudo-periodic time envelope.[41] At the outset of a tone, the upper partials first evolve, followed by the lower components which tend to develope over a longer period of time.

Meyer used octave filter oscillograms to analyse the initial portion of a tone. The transient duration was shown to last around 25mSec., followed by a pseudo-stationary condition lasting another 200mSec. Transient duration was not affected by any style of playing.[42]

THE GUITAR

The guitar represents the plucked string group. Basically, there are many physical and acoustical similarities between the guitar and the violin. This is due to the corresponding body shape and the presence of the rose. On the other hand, the absence of a sound post on the guitar forms a major acoustical difference.

Jansson examined the resonances of the top plate and found that the guitar featured symmetrical vibrational modes, unlike the assymetrical patterns found for the bowed string group.[43] Thus, one can find an equal amplitude distribution around the mid-line axis of the top plate. Jansson found that in the low-frequency region of the air resonance, i.e., 100Hz., the guitar acts as a simple source radiating in an omnidirectional pattern. As the first top plate resonance is approached (slightly less than an octave above the air resonance) a doublet vibrational pattern exists that is symmetrical about the mid-line axis.

I. Firth compared the guitar to a bass reflex loudspeaker system.[44] He found that the rose acts as an air port and thus is responsible for the increase of sound-pressure level for the lower frequency range. At frequencies below the Helmholtz resonance, the rose and the top plate exhibit a phase differential, effectively attenuating the lowest register by 12dB./8ve. On the other hand, a significant increase in level is found around the frequency of the Helmholtz resonance. Thus one may anticipate an «exagerrated», «boomy» quality, when a microphone is placed close to the rose. In addition, in a manner analogous to the piano, the guitar produces a waveform devoid of a real steady-state portion.

CHAPTER 4

A COMPARATIVE METHOD OF EVALUATING RECORDED TIMBRES

INTRODUCTION: MUSICAL TIMBRE AND VOWEL COLOUR

An exploration of acoustical phonetics provides information which can be very useful in establishing a method of evaluating recorded timbre. Historically, linguists have presented a comprehensive picture of the acoustical attributes of timbre which is useful to this study.

Since the time of Helmholtz, vocal research has clarified the relationship between the frequency shape and the resultant, tonal colour.[1] For example, resonant characteristics of the vocal tract behave much the same way as the body of a violin. For each vowel sound the subralaryngeal cavity changes shape and size altering cavity resonance patterns. Acting like a low pass filter, the cavity accentuates sound energy at certain frequencies which lie close to the main resonances while suppressing more distant ones. Areas of high energy, called formants, become the identifying acoustical signature of each vowel.[2]

As stated before, a musical instrument's timbre can also be represented by its spectral envelope. Presumably, the identifying elements of musical timbre, such as vowel colour, are determined by certain invariancies in acoustical structure. Although the determination of invariant acoustical features of timbre would be useful, such a study remains beyond the scope of this paper. Instead, this work outlines the similarities between vowel colour and musical timbre to serve as a basis for a method of timbral evaluation.

This chapter opens with a brief overview of the articulatory differences that characterize vowels by physiology. The differences in the manner of articulation are responsible for a vowel's phonetic classification. The acoustical features of each vowel type are then examined in order to distinguish basic formant structures, against which future comparisons with musical timbre can be made. Lastly, an attempt to incorporate acoustic-phonetic theory with descriptive verbal terms is seen as a simple, yet effective, method of categorizing recorded musical timbre. This method serves as the basis for the evaluation of contact pickup placements conducted in the experiment later on in this study.

ARTICULATORY DESCRIPTION OF VOWELS

The larynx, pharynx and mouth cavity collectively form the vocal tract, which may be compared with the resonating body of a violin. The source of vocal sound originates when a stream of air from the lungs flows across the vocal folds. Pulsation of the folds (analogous to the vibrating string), produces a fundamental frequency. The upper partials of this tone decrease uniformly with frequency at a rate of 12dB/8ve.[3]

In the previous discussion, it was noted that a larger instrument body could be associated with lower resonant frequencies. It also holds true for the voice. Since the size and shape of the vocal tract can be varied by the manner in which the vowel is articulated, the spectral envelope of a vowel can vary from speaker to speaker.

In order to describe vowels systematically and avoid confusion between vowel types, a descriptive system was devised by linguists taking into account the articulatory process of vowel production. Essentially, it states that vowels may be described by: a) the height of the body of the tongue; b) the front-back position of the tongue; c) the degree of lip rounding.[4]

Vowels produced with the body of the tongue near the roof and towards the front of the mouth are described as high-front vowels. An example of this type of vowel is (i) as in «feed». The other basic vowel types are: a) low-front (æ) as in «had»; b) high-back (u) as in «who»; and c) low-back (ɑ) as in «father».

ACOUSTICAL ATTRIBUTES OF VOWEL COLOUR

Jansson likens the entire vocal mechanism to a low pass-filter whose output function is defined as $U(w) = G(w); H(w)$; where $G(w)$ is the input or source function and $H(w)$ is the frequency response or transfer function.[5] This formula is the frequency transform presentation of the source-filter model, and is the basis for present day timbral investigations.

The major influence on vocal timbral quality is the resonance or formant structure of the vocal tract. Sundberg found that standing waves in the oral cavity can be linked to the formation of formants.[7] Practically speaking, the vocal tract is similar to the conical cylinder of a reed instrument, exhibiting standing wave patterns at 1/4 ; 3/4 ; 1 1/4 ; etc. Thus, Sundberg calculated that, for an average male vocal tract 17.5 cm. long, formants exist at 500Hz., 1.5KHz., 2.5KHz., and 3.0KHz.[8]

Since the formant envelope is a result of the complex interaction between the various articulators and vocal cavities, each vowel spectrum will contain a unique resonant shape. Fig. 1 demonstrates the general shape of the first three formants for the vowels utilized in this study.

There are a number of ways one can hear the changing resonant frequencies produced by each vowel. For example, if the vowels (i)-«heed»; (ɩ)-«hid»; (ε)-«head»; (æ)-«had»; (ɑ)-«hod»; (ɒ)-«hawed»; (ɔ)-«hood»; (u)-«who'd»; are whispered, one will hear a continuous series of sounds representing the descending pitch of the second formant.[9]

Another method is to reproduce each vowel in a low creaky voice.[10] This reduces the effect of the vocal-cord frequency and allows the changing first-formant frequency to be distinctly heard. It is easiest to do this on the vowel (æ)-«had» and then work up to (i)-«heed» or to (u)-«who'd». As one moves from (i)-(æ) (i.e., «heed»-«had») the pitch is heard rising while movement from (æ-u) (i.e., «had«-«who'd») produces a descending pitch.

Although the vocal tract has over four main resonances, only the first two are considered important for the recognition of vowel type.[11] In one study, Slawson found that: a) a shift of frequencies for the lowest two formants results in a large difference in quality; b) a similar shift in the fundamental pitch produces smaller differences; c) the third formant increases the «naturalness» of the vowel colour.[12]

In addition, it was demonstrated that formant shifts in the (æ); (ɑ); and (ɔ) vowels produce greater quality differences than exhibited by the vowels (i); (o); (u), while a nasal quality in the vowels (æ); (ɑ); (o) (ɒ) is linked with a resonance around 1.2KHz.[13]

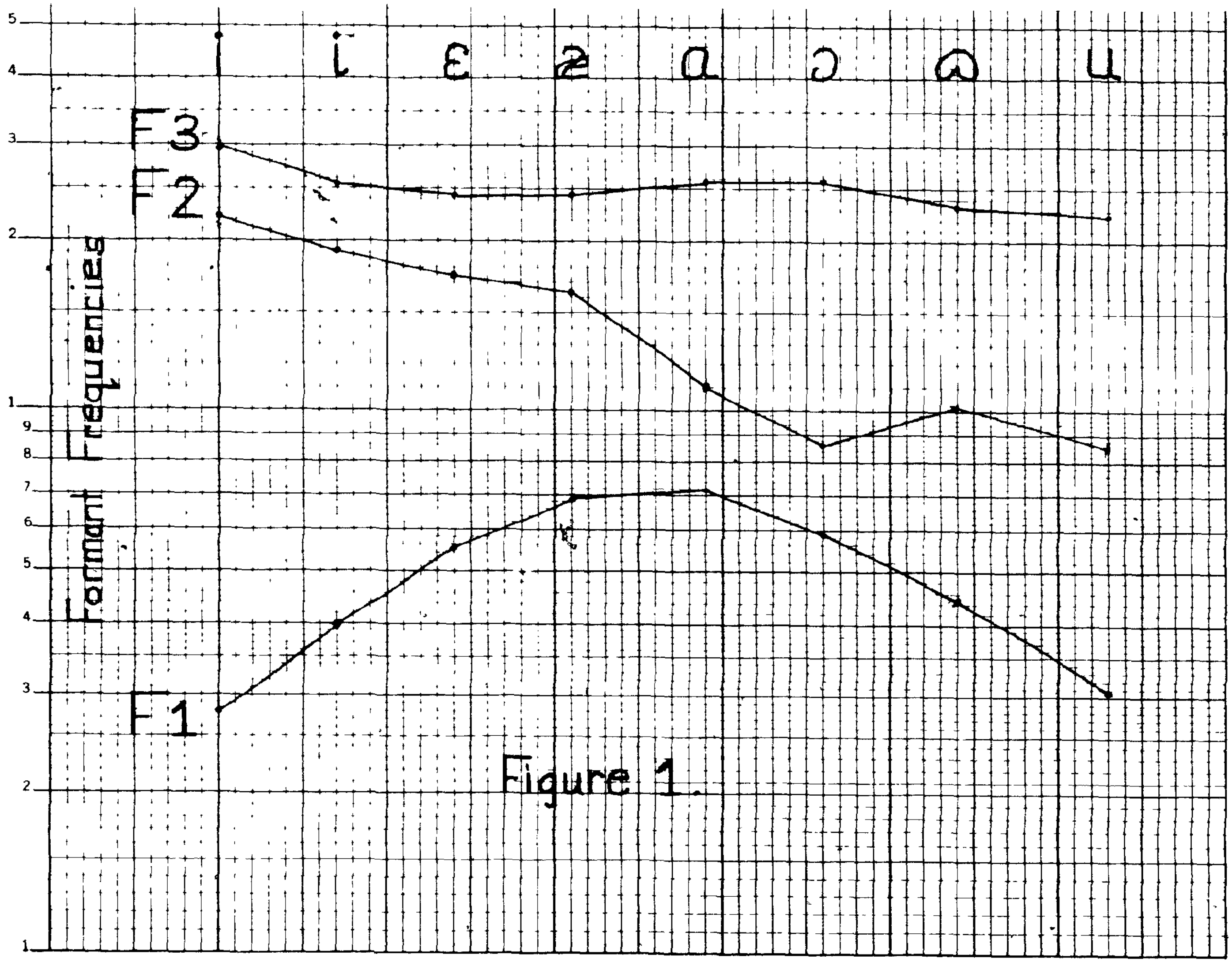


Figure 1.

The question whether or not an acoustically based phonetic model might serve as a basis for a descriptive language in the recording studio is worthy of consideration. For example, we have seen that both vowel colour and musical timbre share distinct acoustical features. Certainly, for sound recording, the establishment of a descriptive language derived from acoustic-phonetic theory would clarify discussions dealing with recorded timbre. Although the topic has been generally neglected by sound engineers, there is much acoustical evidence to support such an undertaking. For example, Slawson states that:

> «. . . in musical sounds with fairly pronounced broad spectral peaks the complex of auditory attributes that make up what is known as musical 'colour' are identical with the auditory attributes of vowel 'colour'. 15

Moreover, in a recent paper devoted to new compositional techniques, Slawson draws on the practicality of utilizing acoustic phonetic models for the development and control of musical timbres.[16] By filtering the formant envelope of synthesized sound masses (in a manner corresponding with vowel formant structues), a strong tonal resemblance with desired vowel types can be created. This way, composed musical timbres share acoustical and tonal features with «open», «acute» or «lax» spoken vowels.[17]

Recently, the formant or source-filter model has been adapted in studies on musical timbre.18 In his work on the auditory perception of musical timbre, Grey suggests that the source-filter model provides the most complete means of understanding the perception of a spectral envelope.[19] This model, based on psycho-acoustical laws,[20] provides objective proof of the natural correspondences between musical timbre and vowel colour.

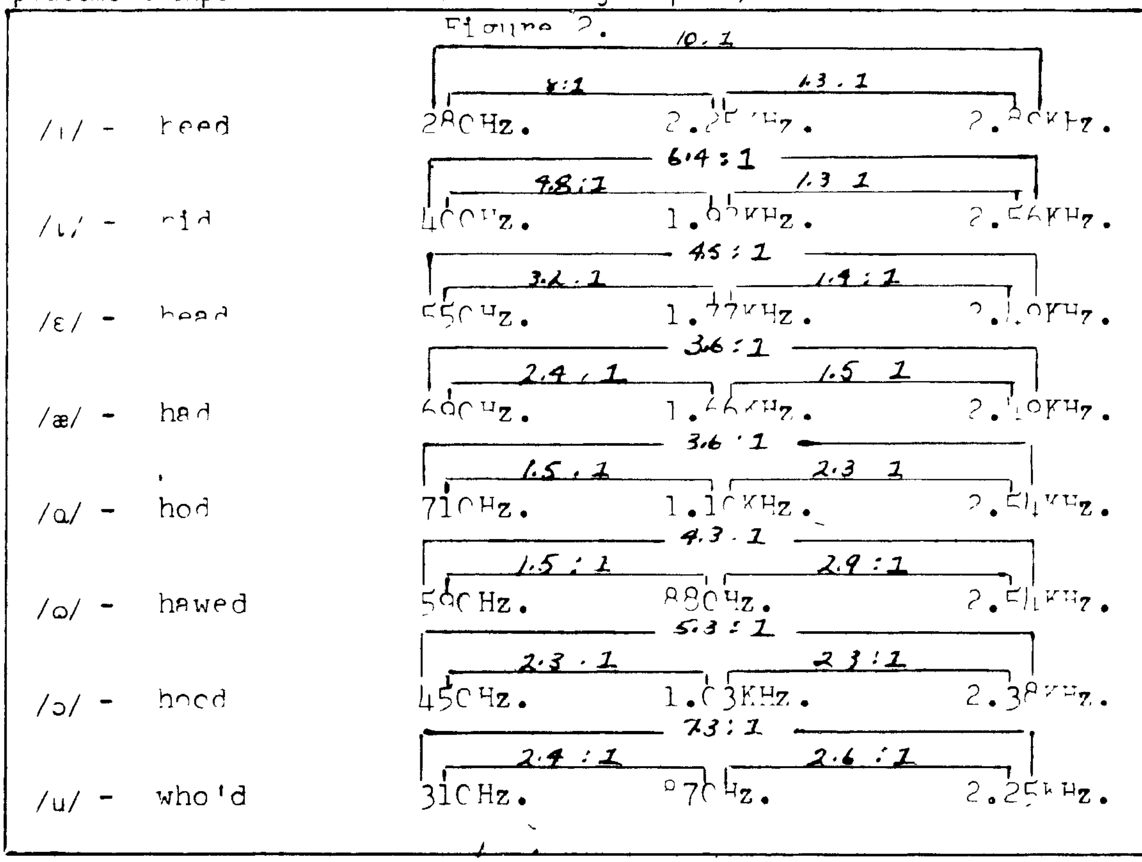
But this is not to say that every musical sound will find a perfect correspondence with one vowel type, but that, in a majority of cases, such analogies help to categorize and describe recorded timbres more fully.

With respect to the application of contact pickups, it would be more correct to say that the timbre of an instrument can be equated with many vowel types. In any one instrument the analogous vowel-identities will depend upon the complex relationship between: a) the manner of articulation (i.e., pizzicato, col legno, plectrum, etc.); and b) the place of articulation (i.e., near the bridge, neck, top or back plate, etc.). Moreover, instruments do not generally exhibit fixed formant structures, but contain shifting spectral energy relative to the fundamental.[21]

In order to normalize this situation for the placement experiments in the next chapter, each recorded timbre is acoustically characterized according to its formant ratio. In this manner, a direct comparison can then be made with similarly structured vowel types. For example, suppose a spectral analysis of a tone reveals three large resonant peaks at 220Hz.; 528Hz.; and 792Hz. Then, by calculating the ratios between each value, one finds that they resemble formant ratios of the low front vowel (æ)-«had» (i.e., F2: F1 = 2.4:1; F3: F2 = 1.5: 1; F3: F1 - 3.6: 1).

Keeping in mind that the most significant timbral information is established by the first three formants, a chart of eight American/English vowel types along with the main formant frequencies has been prepared.[22] As these are typical of vowels used in North America, they will provide the principal vowel-identity categories to which recorded timbres then may be compared.

Figure 2 illustrates the eight vowel types with their formant ratios. (These will be utilized to describe the recorded timbres produced in the placement experiments in the following chapter).



VERBAL DESCRIPTION OF MUSICAL TIMBRE

It seems prudent that a repertoire of specific recording terminology (i.e., «bright», «nasal», «constricted», etc.) be established which would clearly delineate certain features in recorded timbres. Along with vowel-identity (i.e., (ı), (æ), (u), etc.), such terms would enable a fuller characterization of a sound in a manner clearly understood by non-technical participants.

Historically, it would appear that there have been a number of scientific sources from which a specialized recording language might develope. For example, in an attempt to correlate subjective tonal qualities with objective spectral analysis, Helmholtz expressed psycho-physical relationships of complex musical tones in verbal terms.[23] The terms «rich and splendid» indicated a tone in which the low partials (i.e., up to the sixth harmonic), were moderately loud, while an absence of upper partials resulted in a «sweet and soft» timbre. A spectrum containing only uneven numbered partials produced a «hollow» sound. A «nasal» quality was deemed to exist when a large number of odd upper partials were present. Finally, timbre was said to be «rich» or «poor» depending on the strength or weakness of the fundamental pitch.

More recently, Yankovskii shows that an expression of musical timbre based solely on objective data is insubstantial at best.[24] In his work on violin tone, Yankovskii attempts to establish definite and accurate verbal descriptions based on physical observations. By comparing the response of various violins in third octave frequency bands with tone quality assessments of musical experts, Yankovskii was able to verbally characterize the timbre of these violins in the following manner:

1) Classical mean (soprano) - correlates with a dome shaped spectrum with its principal maximum at 1.25KHz. In addition, peaks of gradually increasing amplitude were found at 250, 500 800, and 1.25KHz.

2) Bright - is characterized by fairly strong frequency components between 2.5KHz.-4.0KHz.

3) Noble - contains a large peak at 500Hz. with a smaller peak at 800Hz.

4) Nasal - shows presence of a sharp peak around 1.6KHz.-2.0KHz.

5) Tight (thin) - forms a plateau from 500Hz.-6.3KHz. with a trough in the middle of band. A wide and deep trough creates a «constricted» sound.

6) Piercing - contains pronounced high frequency components around 4.0KHz.

7) Trebly - exhibits a deficiency of partials below 500Hz.

8) Contralto - produces a broad peak around 250Hz.[25]

In order to provide only essential acoustical data for quality assessments, Yankovskii divides the audio spectrum into four main frequency zones a) 200-900Hz.; b) 900-2.2KHz.; c) 2.2KHz.04.5KHz; d) 4.5KHz. and the above.[26] The author concludes that all timbral qualities can be indexed according to the relative strength and position of upper partials within these four zones.

For example, Bright tones are typified by a dominance of energy in the 2.2KHz.-4.5KHz. zone. «Thin» or «tight» timbres exhibit more energy above 4.5KHz., while a deep «contralto»tone demonstrates greater amplitude in the 200-900Hz. zone.

In a recent article on the dimensions of listening tests, F. Toole, discusses a study by Gabrielsson and Sjogren, who conclude that there are only eight perceptual dimensions which can «claim reasonable statistical independence»[27]:

Clearness/distinctness
Sharpness/hardness versus softness
Brightness versus darkness
Fullness versus thinness
Feeling of space
Nearness
Disturbing sounds
Loudness

Another study was conducted by Bartlett, who, after investigating the tonal effects of close microphone setups on various instruments, correlated spectral features with simple descriptive terms.[28] On an acoustic guitar, he noticed that a «very bassy, thumpy, full» sound corresponds to a great boost in the 80-300Hz. area, while very little energy is found above 1.0KHz. A timbre «lacking presence» demonstrates a boost from 80-200Hz., with a trough from 200-1.2KHz. «Weak» timbres are related to a lack of strength in the mid-range (i.e., from 300-650Hz.).

Moreover, terms such as «bassy with good presence» refer to a substantial boost from 80-200Hz.; a considerable dip at 650Hz.; and a smaller emphasis from 1.5KHz.-2.5KHz. A sound described as «naturally bright with clear transients» exhibits a slight boost from 80-150Hz; a slight trough from 150-800Hz.; and a gradual boost from 2.0KHz.-10.0KHz.

In general, terms such as «warm» and «full» tend to correlate with an increase of bass frequencies, while a «thin» or «constricted» tone is associated with troughing in the lowest register. Nasal timbres are attributed to a sharp peak above 1.5KHz., while «trebly» or «harsh» timbres are often linked with an emphasis in the 1.0KHz.-4.0KHz. range.

In the quest for a more effective model of timbral description, Meyer makes use of vowel associations which serve to identify tonal attributes of sound.[29] For example, «sonority» is defined by the strength of the energy in the (u) and (o) formant regions (i.e., from 200Hz.-400Hz., and from 400Hz. 600Hz., respectively). A «powerful» timbre demonstrates great energy within the 800Hz.-1.20KHz. band, representing the first formant region for the vowel (a). A «pungent» quality is found in tones exhibiting strong peaks between 1.0KHz.-1.2KHz., while a nasal timbre is perceived when peaks occur around the 1.2KHz.-1.8KHz. area. The author designates two areas, i.e., 1,8KHz.-2.6KHz. and 2.6KHz.04.0kHz, as being most important for tonal «clarity» and «brilliance».

SUMMARY

The utilization of vowel analogy with selected verbal terminology, provides an important advantage for the categorization of recorded sounds. In this study, a method is put forward requiring that the listener classify each timbre according to one of the eight vowel types previously discussed. In this manner, each recorded timbre assumes an acoustically and tonally unique vowel-identy.

In addition, once the vowel-identity has been established, a descriptive term is used to fully characterize the sound quality. Bearing in mind previous attempts to associate descriptive verbal terms with objective data, the following list will be used to aid timbral characterization of stringed instruments, in the placement experiments following this chapter. The frequencies quoted are in reference to the violin. In most cases, these frequencies will accurately describe the spectrum information for the descriptive term. Only in the double bass and cello will these values be lower.

Full/Solid - strong fundamental and lowest six harmonics

Bright/Trebly - strong high frequencies, i.e., 1.0KHz.-3.0KHz.

Open/Clear - strong 800-2.0KHz. area.

Sharp/Harsh - strong peaks above 1.5KHz.; weak bass.

Present - slight emphasis of 1.5KHz.-3.0KHz. area.

Nasal - strong peak between 1.0KHz.-2.0KHz.

Thin/Constricted - broad emphasis on upper mid-range, (i.e., 500-800Hz.); weak bass.

Bassy/Soft/Dull - emphais on lower mid-range; lack of high harmonic energy.

CHAPTER 5

INTRODUCTION: EXPERIMENTAL DESIGN

Preliminary spectral viewing of a wide range of notes (played in a number of ways, i.e., pizz., bow, plectrum, finger picking) demonstrated that it was possible to select one tone that would sufficiently represent the timbral balance of the instrument. The examination also focused on the lowest register, since amplitude variations of harmonic components are more readily seen. Limiting the amount of data in this way allowed a more in-depth study to be rendered. The spectral analysis for each instrument may be found in the appendixes.

For each acoustical instrument tested, between eight and eleven pickup points were chosen. A professional quality condenser microphone (Neuman U87 set in the omni-directional position) was also utilized for comparison.

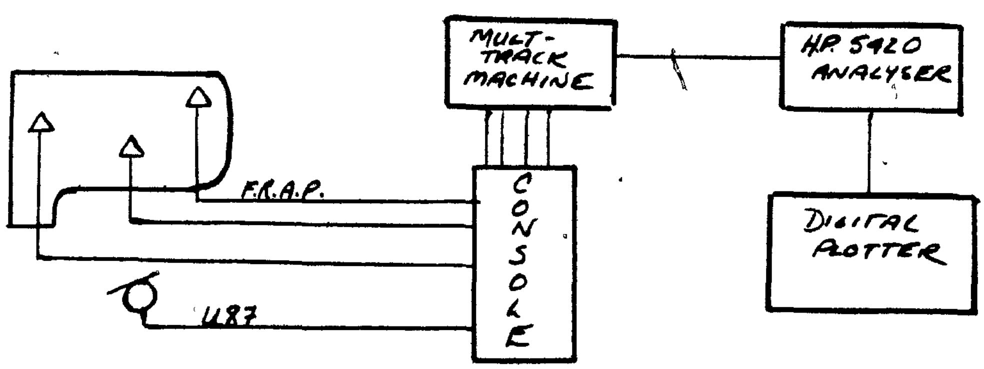
A group of four pickups and one microphone was employed at a time, with the information being stored on a twenty-four track tape. This operation was repeated until the desired number of samples were taken. Storage in this way facilitated comparative testing between placements.

Studies of the vibrational characteristics of each instrument determined the choice of pickup placements. Timbral changes were solely a result of the instrument at the pickup point and not caused by any external equalization. All recording was done in a professional studio environment, with a reverberation time of 0.4 seconds.

Recorded timbres were evaluated by spectral analysis and then correlated with subjective listening tests. As previously stated, these subjective tests were based on vowel categorizations.[1] In this way, listeners characterized the various recorded timbres with specified terms and vowel types.

METHOD OF ANALYSIS

Frequency and time analysis was carried out on a Hewlett-Packard Digital Signal Analyser, model 5420A. The selected tone was averaged in order to diminish variance. Sampling time for each note was 20 mSec. and consisted of 256 data points (between 5 and 10 averages were taken). Analysis in the frequency domain was derived by F.F.T. of the time domain. The bandwidth was fixed between 50 Hz.-12.8KHz., for the violin, viola, piano and guitar, while a bandwidth of 3.2KHz. was selected for the cello and double bass. Observations of the initial portion (1 sec.) of the tone was conducted as well. In this case, band-selectable analysis of each frequency provided a long enough time-record length to capture the entire transient. Expansion of the initial second portion of the analysis clarified the results. Data from these measurements were then plotted on a logarithmic frequency and amplitude scale.



RESULTS: VIOLIN

FREQUENCY ANALYSIS

A total of eight contact pickups were arranged on the body of the violin in the manner shown in the Figure 3. For comparison, a Neumann U87 condenser microphone (omni-pattern), was positioned approximately 2 meters from the performer at a height of 2.5 meters. The violinist was asked to play the open «G» string (i.e., 296Hz.) in a bowed, non-vibrato manner. The note was played at a medium-forte level and held for approximately 3.5 seconds.

Spectrum analysis of the violin tone shows that the first formant area varied from 400Hz.-600Hz. When the first formant was either 400Hz. or 600Hz., the second formant measured at 950Hz. There were two cases, i.e., placement △7 and △3, which exhibited a first formant of 550Hz., and second formants at 1.9KHz. and 700Hz., respectively.

In the investigations by Meyer and Woszczyk,[1] dominant low-frequency radiation from the back plate was found to create a dark, singing quality reminiscent of the low-back vowel (ɔ). However, with the greater selectivity provided by the pickups, a small region was found that reproduced brighter timbres corresponding to the low-front vowels (i.e., (æ) - (ɛ)). This timbre was produced by placements △5 , and △7 , arranged to the left and right (respectively), of the vertical mid-line

Moreover, it was discovered that back-plate pickups placed near the vicinity of the sound post demonstrated brighter timbres than ones located at more remote positions. The action of the sound post serves to transmit more high-frequency vibration amplitude to the back plate and thus to the immediate area. It is interesting to note that the manufacturer of the pickup recommends a back plate placement directly over the sound post,[2] (corresponding to placement △5).

The analysis of pickup 5 showed a very weak fundamental along with strong peaks at the second and fifth harmonics. The particular «edge» was attributed to the high amplitude of the fifth harmonic (950Hz.). In comparison, placement △7 provided a stronger fundamental component, while higher formants exhibited lower amplitudes. In addition, both of these back placements demonstrated a broad resonance around 500Hz. and 1.0KHz.

Less «bright» and somewhat «thinner» timbres were found for placements △8 (placed on the side rib); △2 (placed on the front plate between the «f» holes); and placement △9 (i.e., the microphone).

The spectral envelopes, derived from these diverse placements, demonstrated identical first and second formant values; the third formant varied slightly. All tones were «bassy», and could be compared with the front vowel (æ).

Analyses of the remaining placements indicated that pickups in close proximity to the «f» holes or to the sound post were generally «brighter» in quality. These placements may be categorized within the low-front vowel group (æ - ɛ).

On the other hand, placements △1 (arranged behind the bridge on the mid-line axis); △3 and △4 (situated on the upper and lower sections of the front plate) produced «dark» and «less full» sonorities. One finds timbres, in this area, exhibiting low-back vowel formant structures (ɑ) - (ɔ).

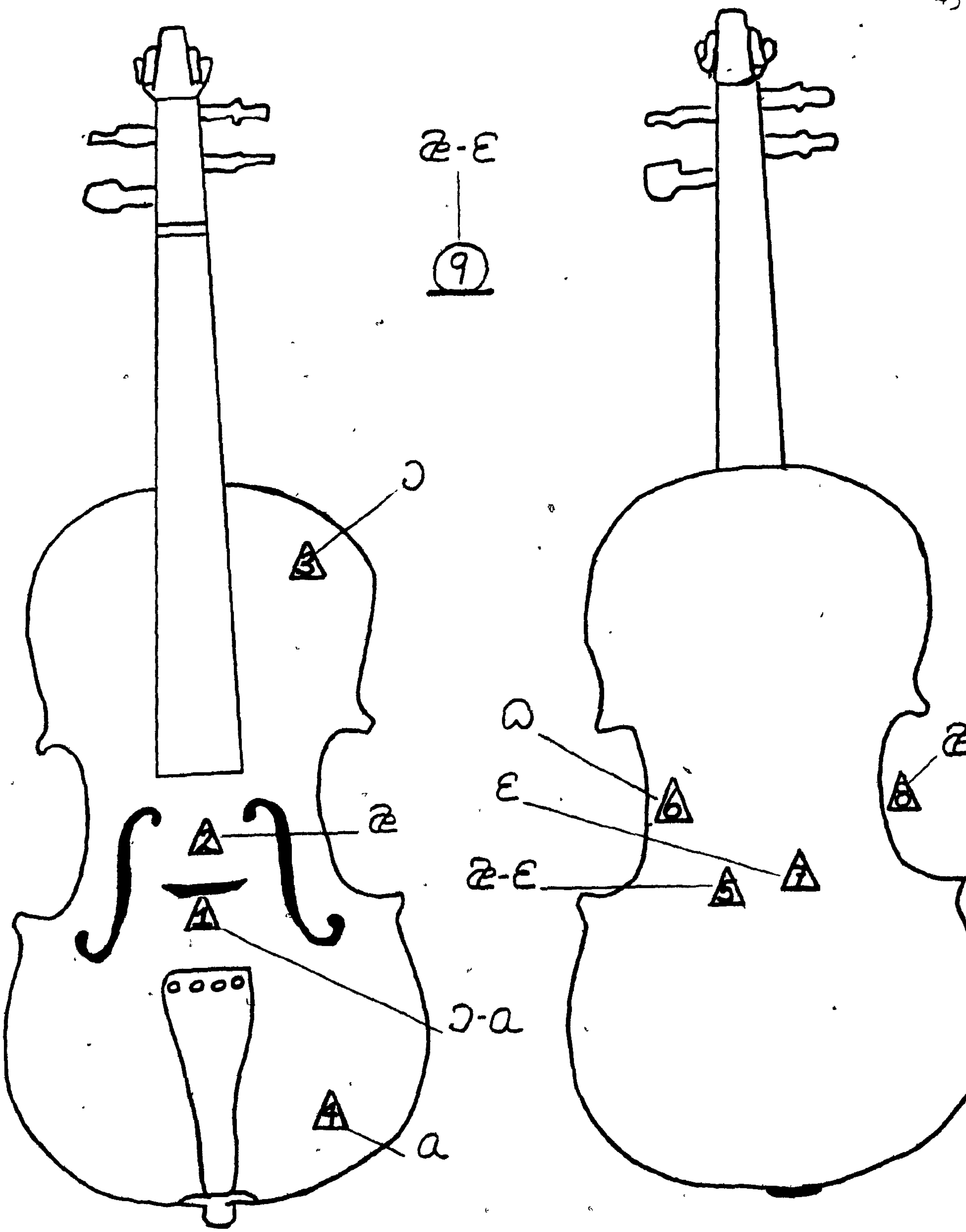


Figure 3 VIOLIN

The «darkest» quality was found for placement △6 (situated on the left side of the back plate near the edge). Due to the emphasis on the lower mid-frequency portion of the spectrum, the timbre may be described as «bassy» or «soft». The envelope shows equidistantly spaced formants resembling the high-back vowel (^{o}).

TIME DOMAIN ANALYSIS

For the seven placements analysed in the time domain, the average duration was 107mSec. The longest transient average (141mSec.) was sampled by the microphone (i.e., placement △9), while placement △1 recorded the quickest time (85mSec.).

The transient analysis of placements categorized in the low-back vowel group (i.e., △1, △4, △3) exhibited faster attack durations compared with the microphone. Furthermore, the time analysis showed considerable instability of the waveform from 600Hz.-750Hz.

A longer attack duration was illustrated by placement △6. This «dark» low-back vowel timbre revealed an unstable 600Hz. component, while the mid-frequency harmonics (400Hz. and 950Hz.) took longer to develope into a steady-state value.

Greater amplitude levels for high harmonics during the attack portion typify the low-front vowel placements △2, △5, △7 and △8. Also included in this group is the microphone placement △9. On the average, these placements displayed long attack durations for the lowest harmonics, with considerable instability between 600-750Hz. During the attack, the microphone exhibited harmonic instability at 550Hz. and 750Hz., with greater levels for the lower harmonics.

Table I offers a summary description of the salient frequency and temporal features found in this placement study.

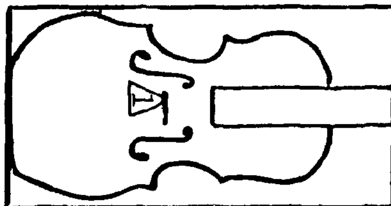
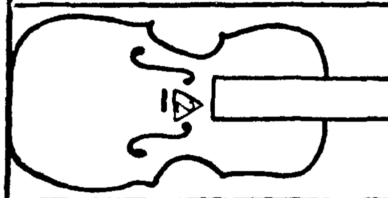
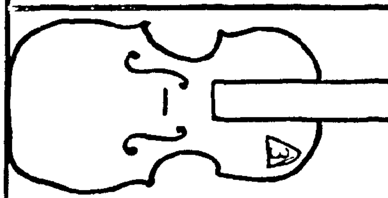
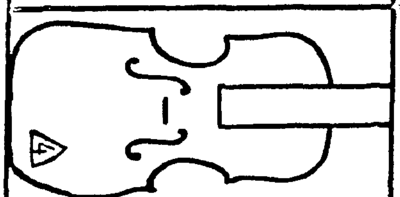
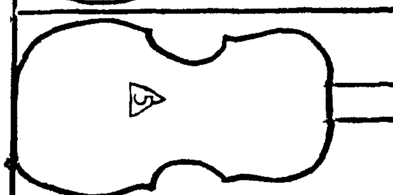
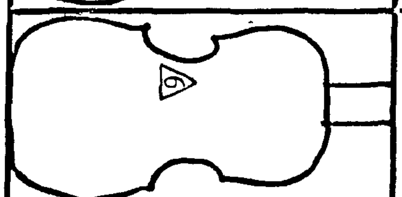
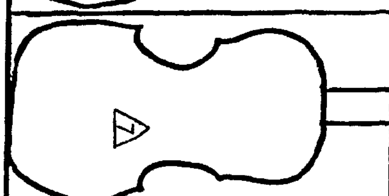
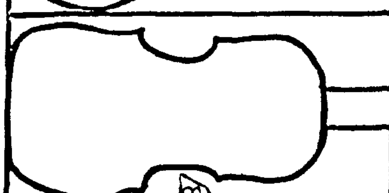
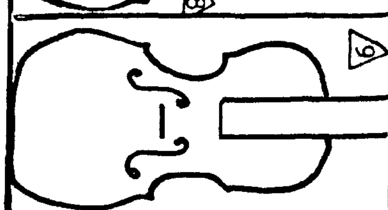
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	ɔ - ɑ	thin/hollow	-weak fundamental -peaks at 600Hz.; 950Hz.; and 2.20KHz. -transient instability between 600 - 750Hz.
	œ	nasal	-weak fundamental -peaks at 400Hz.; 950Hz.; 2.0KHz. -transient instability at 400Hz.
	ɔ	mid-range edge / constricted	_weak fundamental -strong 550-950Hz. area. -boost between 2.0-2.2KHz. -trans. instability for upper harmonics(1.1-1.5K)
	ɑ	medium bright	-weak fundamental -peaks at 600Hz.;950Hz.; 1.80KHz. -trans. instability between 600Hz.-750Hz.
	æ - ɛ	open / medium bright	-weak fundamental -peaks at 400Hz.; 950Hz.; 2.0KHz.
	ɷ	dull / muted	-weak fundamental -peaks at 400Hz.; 950Hz. -strong attenuation above tenth harmonic(2.1KHz.) -trans. instability at 600Hz.
	ɛ	thin / trebly	-strong fundamental -peaks at 750Hz.; 2.1KHz.
	œ	open / bright	-weak fundamental -peaks at 400Hz.; 950Hz.; 2.0KHz. -trans. instability between 600-750Hz.
	æ - ɛ	thin bass / open	-weak fundamental -peaks at 400Hz.;950Hz.; 1.60KHz. -trans. instability between 550Hz.- 750Hz.

Table I.

VIOLA

FREQUENCY ANALYSIS

The investigation of the frequency envelope of the eight recorded viola tones was conducted in the same manner as for the violin. Figure 4 illustrates the arrangement of contact pickups that were utilized.

Analysis of the formant structure along with listening tests indicated that a wide range of colours could be reproduced. Recorded timbres were most consistently categorized in the front-vowel group (æ-ɩ), although darker timbres were also located.

The general trend of the tonal distribution on the viola was consistent with the results found by Woszczyk.[3] Using a close multi-microphone technique, he discovered that back-plate radiation produces a strong 400Hz. component, contributing to a back vowel (i.e., u-ʊ) colour. Likewise, in this inquiry, analysis of contacts placed on the back plate reveals a strong peak around 400Hz., (except in placement △7 where a strong fundamental was accompanied with a lower first formant value). Also, the «harsh» quality found in close microphone arrangements near the neck concurred with findings in this investigation.[4]

In many cases, the recorded timbres also displayed a «nasal» quality. Various authors have ascertained that the «nasal» feature inherent in stringed instrumental tone is related to a strong peak between 1.0KHz. and 2.0KHz.[5] Throughout this examination, placements exhibiting a nasal quality emphasized the third harmonic, accompanied with weak second harmonic. Furthermore, a concentration of energy was observed at 1.55KHz. This feature was most

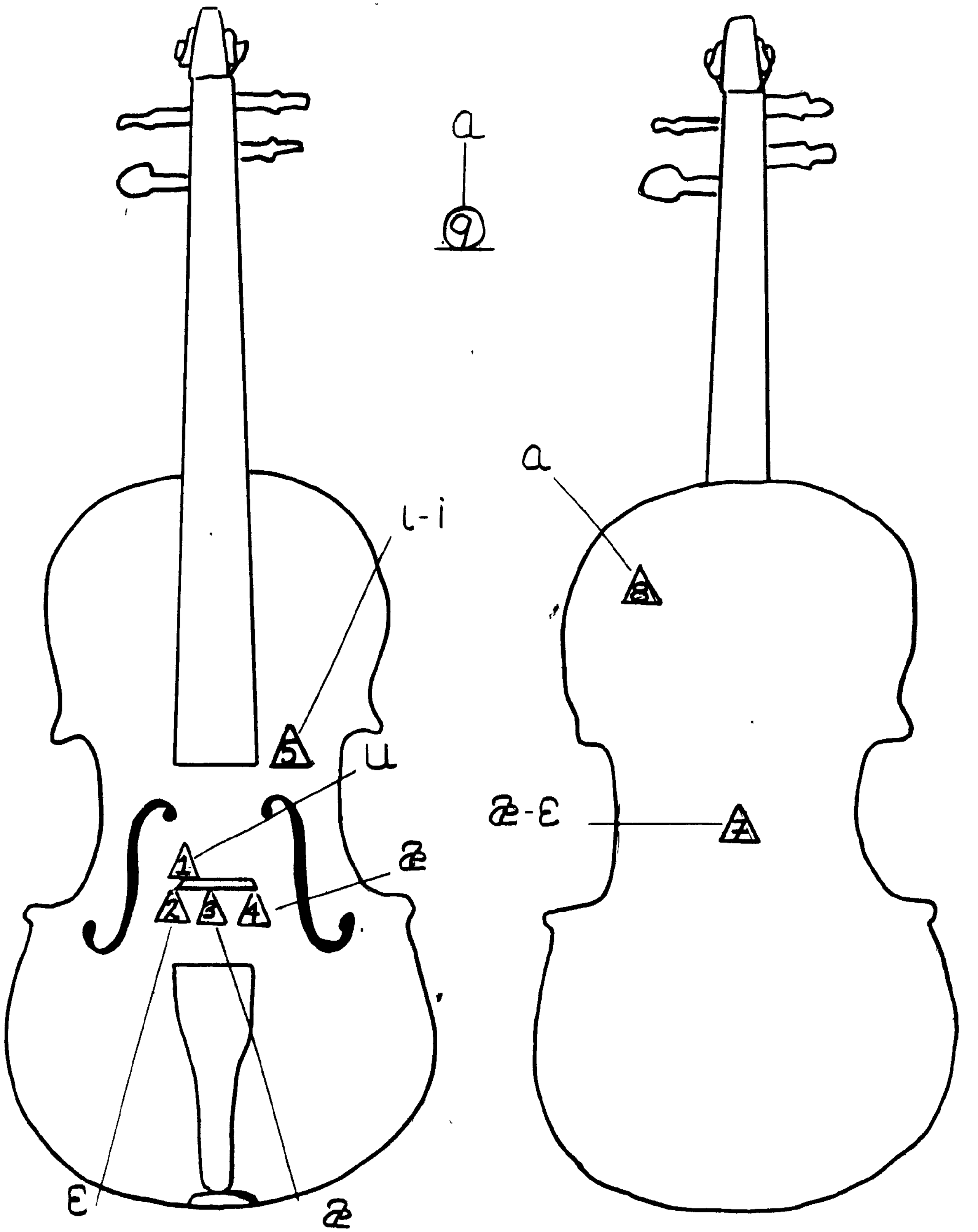


Figure 4 VIOLA

common with the recorded timbres corresponding to the front-vowel group (æ - ɛ).

The darkest recorded timbre was produced by placement △1 , and categorized in the back-vowel group (u). The spectrum showed a strong fundamental followed by high amplitudes for the next five harmonics. A boost in the 2.85KHz.-3.30KHz. region contributes to the tone's «clarity». Listeners described the recorded timbre as having a «full» and «bassy» sound.

Back-plate placement △8 produced a «rough» or «sharp» sound. The frequency analysis indicates a weak fundamental with large peaks at 400Hz., and 650Hz. A significant boost was found in the 1.50Hz-1.80KHz. area. The back-vowel (ɑ) sound of this placement was characteristic of placements near the edge of the back plate and can be found for other stringed instruments.

Pickups △2 , △3 and △4 displayed a variety of timbral changes that occur when contacts are placed just before the bridge. Pickups △3 and △4 were arranged in the middle and to the right side of the bridge, respectively. In the case of △4 , large peaks were found at 500Hz. and 650Hz., with a smaller one at 2.25Hz. A boost in the 1.20KHz.-1.80KHz. area contributed to the «nasal» quality. The formant ratios corresponded to the low-front vowel (æ).

Placement of the pickup towards the middle of the bridge (i.e., placement △3) created a less «nasal» and more «open» sond. In this case, peaks were found at 400Hz., 650Hz. and at 2.10KHz. Compared with pickup △4 there was less emphasis in the «nasal» region (i.e., from 1.0-2.0KHz.).

High amplitude levels for mid-range harmonics were observed at placement △2, situated at the extreme left side of the bridge. Unlike previous bridge placements, the peaks were more distantly spaced (i.e., 450Hz., 1.50KHz.; 2.25KHz.) with strong attenuation of the components above 2.85KHz. Formant ratios for this tone were similar to the front vowel (ε). Listeners characterized this tone as «thin» or «constricted».

Next, an investigation of the placement suggested by the manufacturer of the F.R.A.P. was conducted.[6] Following their instructions, placement △7 was arranged on the back plate near the area where the sound post lies. Spectrum analysis demonstrated that the first six harmonics were strongest. Peaks appeared at 250Hz., 650Hz. and at 3.0KHz., placing this tone within the (æ − ε) vowel category. The timbre was described as being «rounded», «well-defined» and considered to best represent the typical viola sound.

Placement △5 produced the brightest recorded timbre. A great peak at 450Hz. dominates the first ten harmonics. Two peaks, a large one around the 1.50KHz.-2.40KHz area, with a slight one at 3.30KHz., contributed to the «harsh» or «sharp» quality. This timbre corresponded to the high-front vowel group (ɩ − i).

The microphone tone was considered to possess an «open» and «clear» quality, although the low end lacked «definition». Spectral analysis exposed a weak fundamental with strong peaks at 450Hz., and 650Hz. Moreover, in contradistinction to other analyses, the peaks were less exaggerated throughout the spectrum.

TIME DOMAIN ANALYSIS

Transient analysis of the recorded viola tones exhibited average attack durations 20% longer than found for the violin. The longest attack-time average was produced by the microphone (170mSec.), also demonstrating great waveform stability. The other contact placements, however, showed significant instability, especially at the fundamental (150Hz.), fourth and fifth harmonics.

Relatively long attack times were found for placement △1 (categorized in the (u) vowel group). Here the fundamental developed quickly (110mSec.) while the sixth harmonic (800Hz.) evolved more slowly (220mSec.). Somewhat atypical for the viola placements analysed was the minimum amount of instability that was found at the fourth (550Hz.) and seventh (940Hz.) harmonics. Moreover, the stability of the fundamental was unusual, and found only in one other «non-nasal» placement (i.e., △7).

Although placements △9 (microphone) and △8 were both categorized within the back-vowel group (a), the latter exhibited much more waveform instability. This was especially noticeable in the upper mid-range (i.e., from 500Hz.-800Hz.).

Recorded timbres included in the (æ) vowel category demonstrated an unstable fourth harmonic. The most «rounded» tone was also the most stable (i.e., placement △7). Placements △3 and △4 yielded timbres that were perceived as «nasal» and «harsh». Both contained unstable fundamentals and fourth harmonics, while the latter also showed instability at the sixth harmonic.

It is interesting to note that in timbres that were perceived as «bright» or «sharp» the tone contained a great number of unstable components. This was corroborated in the analysis of the front vowel placements, i.e., △2 (ɛ), and △5 (ɪ -ɪ).

A number of conclusions were drawn from this study. For example, it was observed that: a) all tones recorded by contact pickups exhibited shorter attack times than those produced through the microphone; b) transient instability appeared to be greater for the top plate pickups, especially behind the bridge; c) pickups arranged near the bass strings, between the bridge and neck, resulted in a «clear» «full» sound; d) pickups situated near the neck on the top plate produced a «sharp» tone; e) increase of unstable components in the waveform corresponded with increased «nasality» and «harshness» in the sound.

Table II provides a summary description of the main spectral features found in this section.

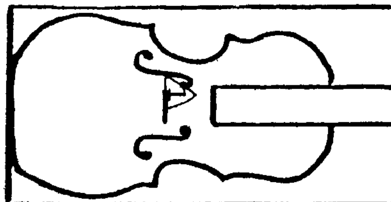
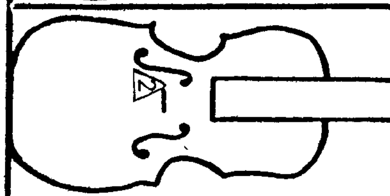
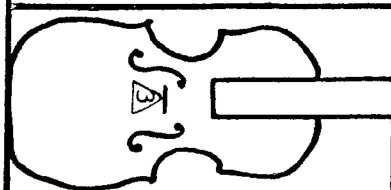
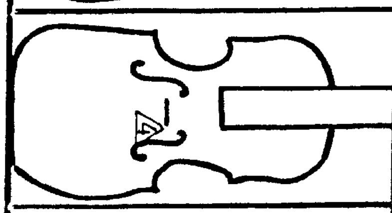
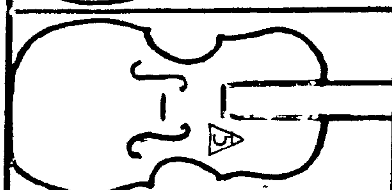
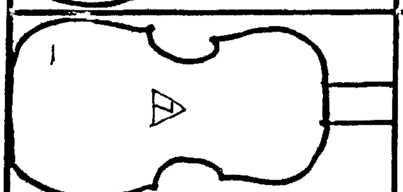
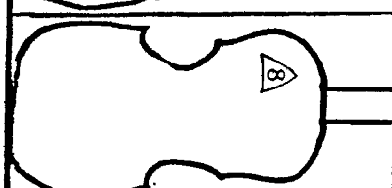
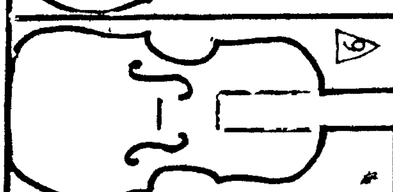
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	u	full bass sound	-strong fundamental -peaks at 250Hz.;650Hz.; -boost in the 2.85KHz.-3.3KHz. -trans. instability-550Hz
	ɛ	mid-range emphasis nasal	-weak fundamental -peaks at 450Hz.;1.50KHz. 2.25KHz. -attenuation after 2.85KHz -trans. instability from 150HZ.-900Hz.
	æ	open / slightly nasal	-weak fundamental -peaks at 400Hz.;650Hz.; 2.1KHz. -boost in the 1.35-1.65KHz -trans. overshoot- 900Hz.
	æ	bright / nasal	-weak fundamental -peaks at 500Hz.;650Hz.; 2.25KHz. -boost in the 1.2-1.8KHz. -trans. overshoot-500Hz.
	ɩ - ı	harsh / nasal	-weak fundamental -peaks at 450Hz.;1.65KHz. 3.3KHz. -boost of 1.5-2.4KHz.area -trans.overshoot-900Hz.
	æ - ɛ	open / round /	-strong fundamental -peaks at 250Hz.;650Hz.; 3.0KHz. -trans.overshoot-800Hz.
	ɑ	sharp / bright / percussive	-weak fundamental -peaks at 400Hz.;650Hz. -boost of 1.5-1.8KHz. area. -trans.overshoot-900Hz.
	ɑ	open / clear / weak low end	-weak fundamental -peaks at 400Hz.;650Hz. -trans.overshoot-250Hz. - " instability-150Hz.

Table 2

CELLO

FREQUENCY ANALYSIS

Along with a microphone, a total of nine placements were analysed in the frequency domain. Figure 5 illustrates the pickup arrangement employed. The cellist was asked to play a legato, non-vibrato tone on the open «C» string (62.5Hz.) for approximately three seconds.

The most significant frequency information for the cello was contained within a 3.0KHz. bandwidth.[7] Analysis of the recorded cello timbres categorized within the back-vowel group (i.e., between (ɔ) - (u)), were characterized by two main formants at 200Hz. and 400Hz. Brighter timbres, corresponding with the front-vowel group (æ - i) also were discovered. In these placements, the recorded timbres demonstrated peaks: a) around 600Hz.; b) between 850Hz.; and c) between 2.1KHz.-2.5.KHz.

An attempt was first made to investigate the placement suggested by the manufacturer of the contact.[8] Therefore, placement △3 was arranged on the bass-bar side of the top plate. In this position, the recorded cello timbre was categorized in the back-vowel group (u), and described as «full» or «solid» in the low end. Spectral analysis uncovered a strong fundamental and second harmonic. A boost in the 500Hz-900Hz. area contributed to the «open» quality.

Other placements yielding «darker» timbres were not considered to be as «full». For example, both placements △7 (ɔ) and △8 (ɑ), produced «thinner» timbres. In the latter, peaks at 200Hz., 412Hz., and 875Hz. were accompanied by a weak fundamental and second harmonic. In the former, a strong fundamental; 200Hz.-400Hz. region and peak at 1.93KHz. combined to provide a «well-defined» low end.

A typical microphone position, in front of the top plate approximately two meters away, was utilized for comparison. The timbre was «thin» and not as well-defined as for other pickups. The analysis shows concentration of energy around 200Hz., and between 300Hz.-900Hz. Harmonics located above this point were attenuated, somewhat reducing the «clarity» of this register.

The back-vowel sound (ɔ-ɷ) of placement 4, was typical of other pickups situated near the edge of the top plate where a fair distance was maintained from the «f» holes. The recorded cello timbre was described as «reedy» and was likened to a «bassoon» quality. At this position, a fairly strong fundamental and 250Hz.-375Hz area were discovered. A marked peak at 750Hz. (so characteristic of the bassoon/trombone formant[9]) was bordered by troughs at 500Hz. and 1.0KHz. A boost in the 1.20KHz.-1.93KHz. area contributed to the «open» quality of this tone.

A similar type of «reedy» yet «oboe-like» sound (corresponding with an higher formant emphasis) was perceived for placement 6. However, unlike the previous placement, this pickup was situated on the back plate in the lower section of the body and exhibited a «bright» quality corresponding with the front-vowel group (æ-ɛ). Spectrum analysis revealed a broad resonance around the fundamental with high amplitude levels for harmonics, between 200Hz.-600Hz. In addition, troughs were apparent at 750Hz. and 2.05KHz., while a further boosting of the 1.87KHz.-2.43KHz. area resulted in added «sharpness».

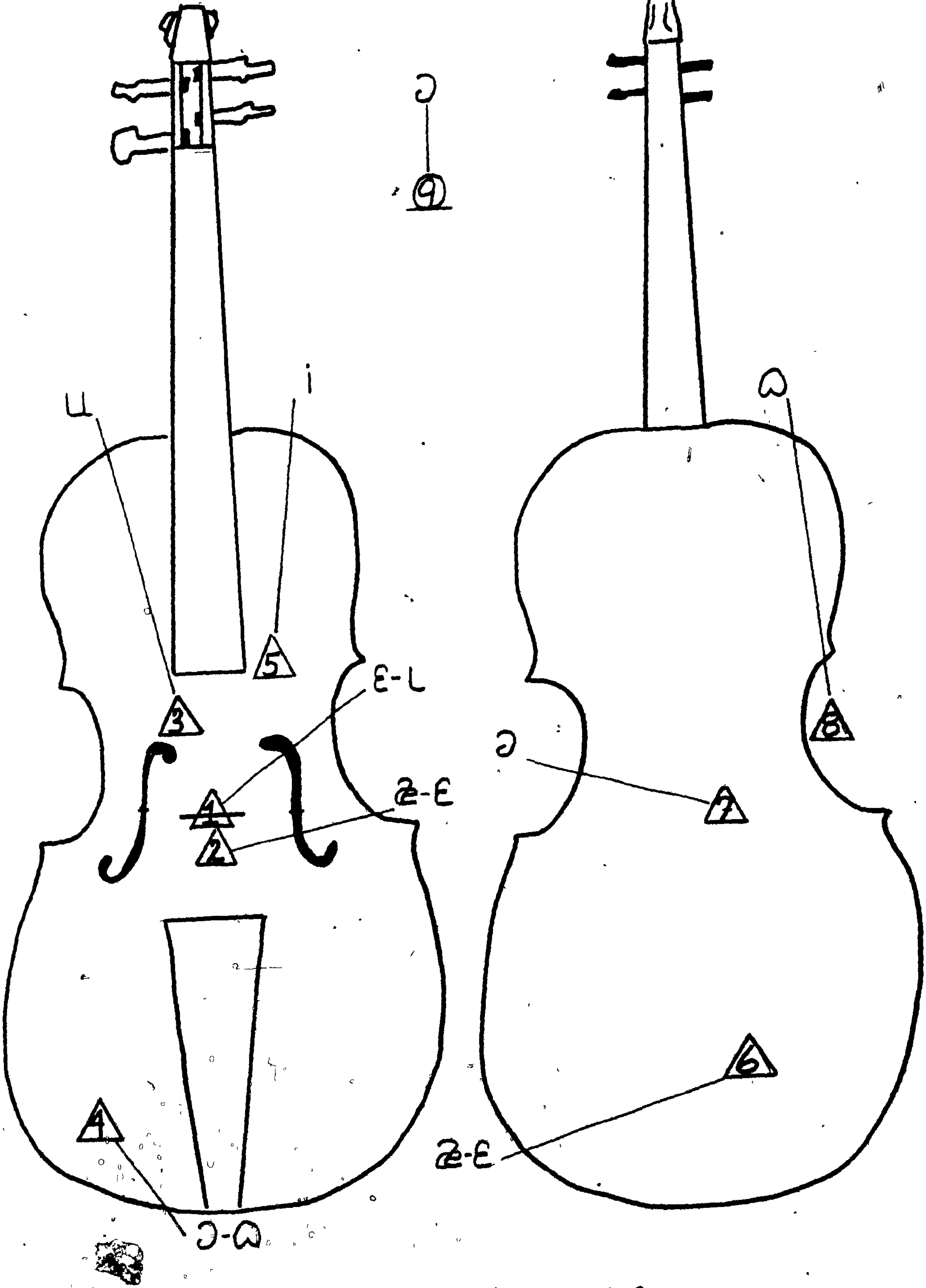


Figure 5 CELLO

In general, a pickup mounted on the bridge instantly responds to the large vibrational amplitude created by the strings, and is unaffected by the filtering action of the body. The result is an undesirable emphasis on the high-frequency end and an uneven amplitude response in the lower region. Since the low-frequency response of pickups employed in this study was shown to be dependent on mounting procedures (Chapter 2), care must be taken to have the pickup firmly mounted to avoid such «harsh» or «strident» timbres.

However, if many channels are available for spectrum balancing, this placement can provide added «brilliance» and «bite» to the recorded timbre. Frequency analysis of placement △1, showed that main peaks occur at 400Hz., 560Hz., 1.75Hz., and 2.30KHz., while significant troughing took place between 150Hz.-375Hz. and at 850Hz. Categorized in the front vowel group (ɛ - i), this placement area was described as «trebly» and «harsh».

Bridge placement △2, situated behind the bridge near the bass bar, is favoured by the F.R.A.P. manufacturer.[10] The recorded timbre produced by this pickup displayed a «bright» quality, without the «harshness» of the previous bridge placement. Moreover, analysis demonstrated more even amplitude levels throughout the harmonics with a stronger fundamental. The main formant at 600Hz. contributed to the front-vowel sound (æ-ɛ).

As discovered in the viola placements, contacts situated near the neck produced the «brightest» quality. For example, placement △5 yielded a «harsh» or «throaty» sound and was categorized in the front-vowel group (i). Examination of the spectrum revealed a strong fundamental and odd numbered harmonics (especially 200Hz., 337Hz., and 475Hz.). In addition, the spectrum showed a considerable energy boost in the 1.56KHz.-2.37KHz. area. The absence of a second harmonic supported previous observations, which conclude that the degree of «harshness» is inversely proportional to the strength of the second harmonic. Thus, the «strident» quality of this placement is partially linked with the weak second harmonic component.

TIME DOMAIN ANALYSIS

Waveform analysis of the open «c» string (62.5Hz.) was conducted for each placement. In comparison with the viola, the cello produced attack durations 60% longer. The analysis also showed more waveform stability, with only a minimal amount of transient overshoot. Therefore, the longer developing waveforms of the cello were more stable than either the violin or viola.

Unlike the transient analysis for both violin and viola, the microphone pickup in this case revealed no unstable waveshapes. Furthermore, the microphone did not have the longest average attack duration. (Placement △8, on the instrument's side held that distinction). In addition, it was discovered that for both contact and microphone placements, the lowest components developed much more slowly than the higher harmonics.

Except for the microphone placement, a number of harmonics had a large number of varying waveshapes throughout their duration. The most persistently unstable components were the fifth and sixth harmonics, (337.5Hz. and 412.5Hz. respectively). Unlike the viola, the cello demonstrated a consistently stable fundamental waveform.

Table III provides a summary description of the main frequency and temporal features found in this investigation.

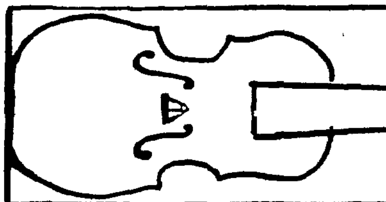
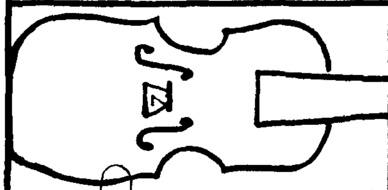
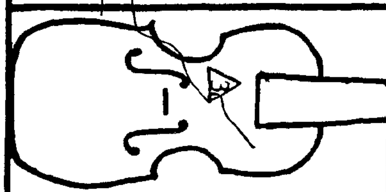
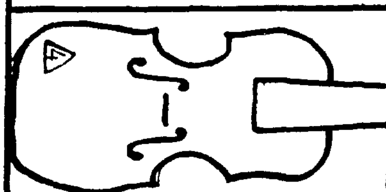
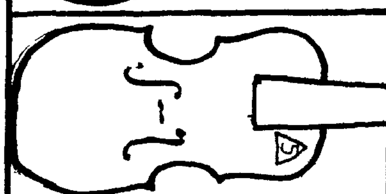
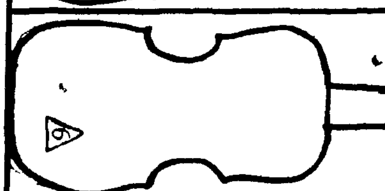
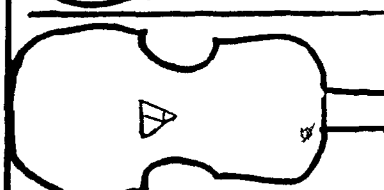
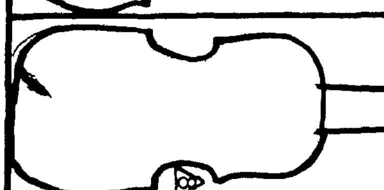
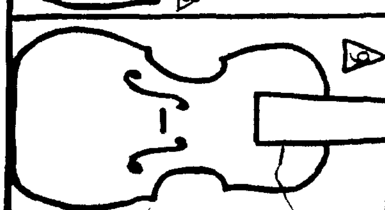
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	ε - ι	harsh / treble / nasal	-strong fundamental -peaks at 400,560,940, 1.75KHz.; 2.30KHz. -trans.instability-337.5, 475.5Hz.
	æ - ε	medium bright / nasal	-strong fundamental -peaks at 400Hz.;600Hz.; 2.25KHz. -trans.instability-337.5
	u	solid low end	-strong fundamental -peak at 137Hz. -boost between 500-900Hz. -trans.instability-337Hz.
	ɔ - ɷ	open / reedy / bassoon-like	-strong fundamental -peak at 750Hz. -boost between 250-375Hz; 1.2-1.93KHz. -trans.instability-412Hz.
	i	harsh / bright	-strong fundamental -peaks at 200Hz.;337Hz. -deep trough at 137Hz. -boost between 1.56-2.37K Hz.
	æ - ε	bright / reedy / oboe-like	-strong fundamental -peak at 875Hz. -boost between 200-500Hz. 1.87-2.43KHz. -trans.instability-412Hz.
	ɔ	thin / hollow	-strong fundamental -peak at 1.93KHz. -boost between 200-400Hz. -trans.instability-137, 462.5Hz.
	ɷ	extremely hollow	-weak fundamental -weak 137,262.5Hz.,750Hz. -peaks at 200,412.5,875Hz -steep fall beyond 1.0KHz -trans instability-412.5 Hz.
	ɔ	hollow / undefined	-very weak fundamental, 137Hz.;and 262Hz. -peaks at 200,262,400Hz. -trans.overshoot-262Hz.

Table 3

DOUBLE BASS

FREQUENCY ANALYSIS

The recording of the double bass offers one of the most formidable challenges for the sound engineer. Since the lowest fundamental (E_3-41.2Hz.) is almost a full octave below the air resonance of the instrument, the double bass has difficulty radiating tones in the lowest register.[11]

The naturally weak projection of the lowest tones compounded with unwanted reverberant sounds in the recording environment, discourages the use of distant microphone setups. Close microphone arrangements also have some drawbacks, for while most frequencies are radiated in a hemispherical pattern around the bass, narrower patterns of directivity still exist for the highest components. In many cases, the resultant recorded timbre suffers from an «ill-defined» or «weak» low end, with an uneven amplitude response for the highest frequency.

Contact pickups, on the other hand, are especially designed for optimum isolation and tonal localization. As noted earlier, contacts consistently ensure good energy transfer in the high end, regardless of the mounting procedure (Chapter 2). Moreover, after some practice, placements can be found that provide an effective means of obtaining a «solid» and «clear» low end to the otherwise naturally «weak» lowest register.

Along with the manufactuer's recommended placement,[12] six other pickups were disposed on the front and back plates. As in previous examinations, an onmi-directional microphone was placed two meters from the performer.

Figure 6 illustrates the tonal variety available through selected contact placements.

Frequency analysis of the recorded bass timbres showed that the first formant varied from 88Hz.-163Hz., while the second and third formants registered between 200Hz.-400Hz. and 500Hz.-750Hz., respectively. Since the comparison with the formant structure of spoken vowels was based on formant ratios, rather than absolute values, these low frequencies did not pose a serious obstacle towards timbral categorization.

A series of pickups arranged over a large area of the back plate were found to emphasize frequencies a little more than an octave above the fundamental. Typically, the more «muted» or «non-open» timbres corresponded with an attentuation of the 400Hz. area, while «brighter» tones exhibited more energy in the 500Hz-1.0KHz. range. These pickups also presented a smaller peak at 1.0KHz. Compared to the front-plate pickups, analysis showed a weaker fundamental.

Back plate placements △5 , △6 , △7 and △8 , all showed a timbral homogeneity corresponding to the back vowel group (u-ɑ). Within this assemblage, placement △5 , situated on the lower belly near the edge, demonstrated the most «solid» definition of the lowest register. Generally, this area of the instrument is quite rigid compared to the middle region of the plate and tends to lessen the boosting effect of the plate resonance on the middle register. Consequently, one can effectively increase the «presence» of the lowest end by moving the pickup toward the edge.

Frequency analysis of placement △5 showed two formant areas between 88Hz.-200Hz., and 280Hz.-400Hz., with very little energy above 500Hz. The

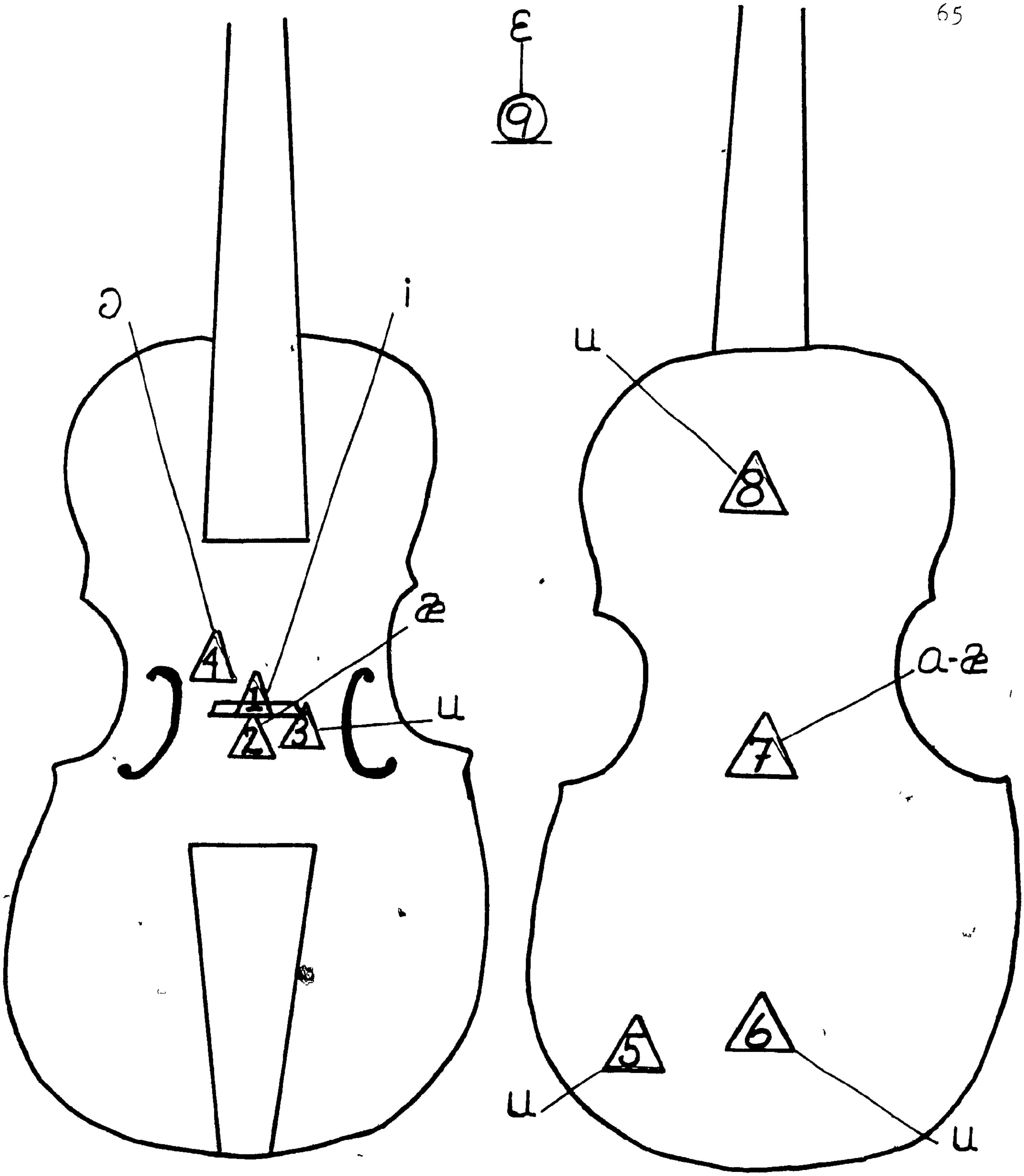


Figure 6 BASS

recorded timbre was categorized within the (u) back-vowel group.

Disposition of the contact at placement △6 resulted in a «muted» or «dull» quality. High-frequency components (i.e., above 500Hz.) are attenuated, resulting in a «non-open» sound. Outside of the main resonant peak at 200Hz. there are no strong partials in the low end.

As discovered in the previous sections, pickups arranged around the sound-post area of the back plate produced «brighter» timbres. For example, placement △7 was described as «open» or «clear» and categorized within the (a-æ) vowel group. Analysis revealed a broad resonance in the 500Hz.-1.0KHz. range.

As the pickups were moved away from the sound-post area, a gradual weakening of the high end resulted in a «muted» and «non-open» sound. Placement △8 occupied a point on the upper region of the back plate, far from the sound-post area. As expected, a severe attenuation of components above 450Hz. produced a «dull» or «bassy» quality. Most of the energy is concentrated within the 88Hz-400Hz. band.

Analysis of the front-plate pickups revealed high-frequency components extending to the 2.5KHz. region. Unlike the back plate, pickups here exposed a much wider timbral range. For example, placement △1 situated on the bridge itself, presented a very «bright» and «open» timbre. In this case, resonances at 378Hz. and 1.17KHz. contributed to an (i) sound. Unlike at most other placements, the fundamental here (37.9Hz.) was the strongest component in the spectrum, resulting in a «clear» or «well-defined» low end.

Placement △2 represents the position suggested by the F.R.A.P. manufacturer.[13] The spectral envelope showed strong peaks at 125Hz., 341Hz. and 2.0KHz. Categorized in the low-front vowel group (æ), the recorded timbre was described as «medium-bright» and «open».

The pickup was then moved behind the treble side of the bridge (placement △3) where it disclosed a «biting» and «full» low-end quality. Spectrally, this timbre was identified by a resonance in the 160Hz.-500Hz. range and by a boost in the 1.0KHz.-2.25KHz. region. The timbre was categorized within the back-vowel (u) group.

In general, timbres recorded by pickups in front of the bridge were considered «duller» and less «solid» in the low end. For example, analysis of placement △4 revealed a weak fundamental and 2.0KHz area, while a strong peak was found at 125Hz. This timbre was identified with the back vowel (ɔ)..

The tone reproduced by the microphone (△9) was judged to be «open» and «fairly bright» without a «well-defined» low end. Analysis illustrated a marked peak around 88Hz., and a weak fundamental. The main formant, situated in the middle-frequency range, contributed to the «open» front-vowel quality (ɛ).

From this examination, it was concluded that: a) back-plate placements off-center and near the edge produced «deep» or «dark» timbres; b) the region surrounding the sound post on the back plate demonstrated «brighter» timbres; c) a «full» low end was found in placements situated behind, rather than in front of the bridge; d) a «full» and «bright» sound was exhibited by placements arranged between the legs of the bridge; e) an «extremely bright» quality was discovered when the pickup was placed on the bridge.

TIME DOMAIN ANALYSIS

For the double bass, a total of six placements were analyzed in the time domain. The average attack time of these placements proved to be 4% longer than that of the cello placements. The back placements produced the longest transient times. The shorter attack durations of the bridge placements resulted in an increase of «brightness» and «presence».

In general, the transients exhibited a great amount of instability, especially at the fourth harmonic (163Hz.). Overshoot was prevalent between the fourth and eighth harmonics inclusive. During the initial 100 mSecs. of the higher harmonics, a small peak appeared, followed by a longer one. Such high harmonic instability was not observed in the microphone analysis.

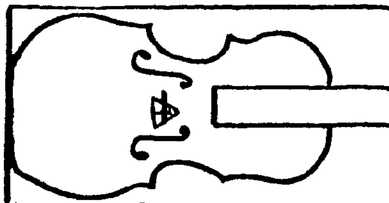
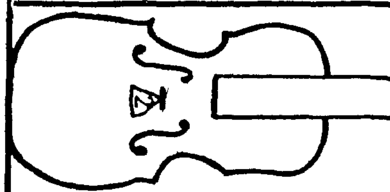
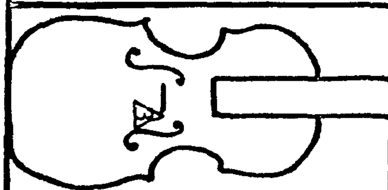
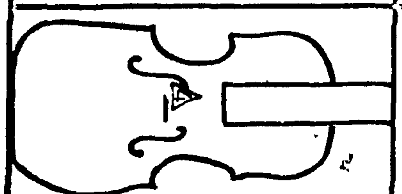
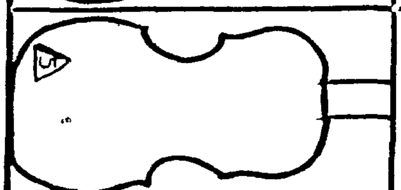
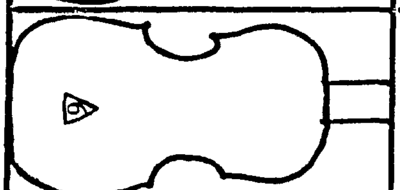
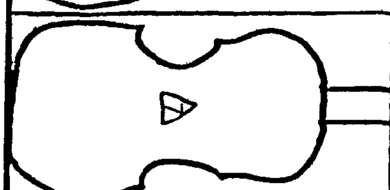
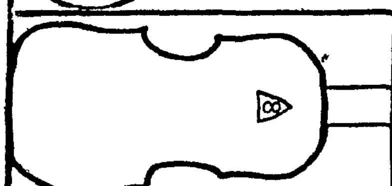
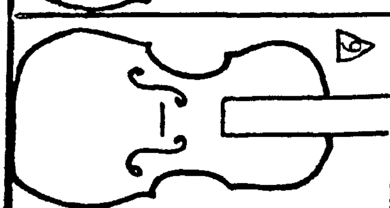
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	ɪ	open / bright / clear low end	-strong fundamental -peaks at 378,1.17KHz. -trough at 125,750Hz. -boost between 1.0-1.43KHz -trans.instability-125-287Hz.
	æ	clear high end	-weak fundamental,265Hz. -peaks at 125Hz.;341Hz. -boost between 1.43-1.70K. -trans.overshoot-200-280Hz
	u	well-defined low end	-strong fundamental -peaks at 125,750,and1.32K -boost between 1.0-2.25KHz -trans.instability-163 - 287Hz.
	ɔ	dull / nasal	-weak fundamental -peaks at 125Hz.;200Hz.; 287Hz.
	ɪu	solid / well-defined low end	-weak fundamental,163Hz. -peaks at 88Hz.;200Hz. -boost between 287-400Hz. -little energy above 500Hz -trans.instability-163Hz.
	u	muffled / muted	-strong fundamental -peaks at 200Hz.;454Hz. -strong attenuation above 600Hz.
	ɑ - æ	dull	-weak fundamental -peaks at 300Hz.;500Hz. -boost between 125-163Hz. -deep troughs at 200,450 Hz.
	u	bassy / muted	-weak fundamental -peaks at 88,163, and 250Hz.;900Hz. -deep trough at400Hz. -trans.overshoot37.8;327H
	ɛ	open / ill-defined bass	-weak fundamental, 350Hz. 500Hz. -peaks at 250,450Hz. -trans.instability-163, 378Hz.

Table IV

PIANO

FREQUENCY ANALYSIS

For the piano, (a seven-foot Yamaha grand), one microphone and ten contact placements were selected for analysis. Groups of pickups were disposed: a) near the hammers; b) in the sound parts; c) on the bass and treble bars, and; d) on the underside of the soundboard. Figure 7 illustrates these arrangements.

A wide range of timbres were uncovered as each individual pickup was examined. The pitch selected for analysis (i.e. C_2 - 150Hz.), falls within a register in which weak acoustical radiation results in «poor bass definition». For example, in his analysis of this problematic register, Meyer found that the intensity maximum shifts from the fundamental to higher-order harmonics.[13] However, specific pickup placements were discovered which diminished this problem by enhancing the fundamental and thus improving low-end «clarity».

Analysis of the most significant sound-shaping formants within the piano spectrum, revealed three distinct frequency divisions. The 300Hz.-550Hz. range, characteristic of the first formant of the high-back vowel (u), was usually accompanied with a strong fundamental producing a «deep», «full» tone. A second division 700Hz.-1.55KHz., corresponded with the first formant for the front vowel (æ). A peak in this area contributed to tonal «fullness» and «openness». A boost in the final division, 2.0KHz.-3.0KHz., produced a «sharp» «percussive» timbre, identifying this sound with the high-front vowel (i).

Microphones are often placed in the sound ports of the piano, in order to gain sufficient isolation and timbral separation. Since these ports offer direct access to the vibrational source, an increased transient «clarity» and «brilliance» is encountered. Analysis of placements △5, △6, △7 provided objective spectral data which then could be correlated with the distinct timbral changes incurred at each port. In this group, the most significant energy was contained within a 2.70KHz. band (i.e., up to the eighteenth harmonic).

Spectral analysis of the timbre produced at placement △7 demonstrated the strongest fundamental of the port placements. A «bright» front-vowel timbre (ɛ – i) was attributed to a broad plateau between 980Hz.-2.7KHz. (i.e., from the sixth to eighteenth harmonic) and peaks at 1.1KHz. and 2.25KHz. Compared with other pickups in this trio, placement △7 presented fewer exaggerated peaks in the «nasal» range, (i.e., 1.0KHz.-2.0KHz.).

Placement △6 was mounted in the centre port near the string crossing. Frequency analysis illustrated that the lower harmonics, especially the fifth (850Hz.) to the tenth (1.15KHz.) were weaker than those of the other port placements. There was also a strong peak at the fourteenth harmonic (2.15KHz.), which added a «nasal» quality to the tone. The pickup produced a back-vowel (ɔ - ω) quality described as «hollow» or «thin».

The final member of this trio, placement △5, was positioned in the second sound port on the treble side of the keyboard. The recorded sound contained a large peak at the sixteenth harmonic (2.4KHz.), with a broad trough between the sixth and tenth harmonics (950Hz.-1.50KHz.)

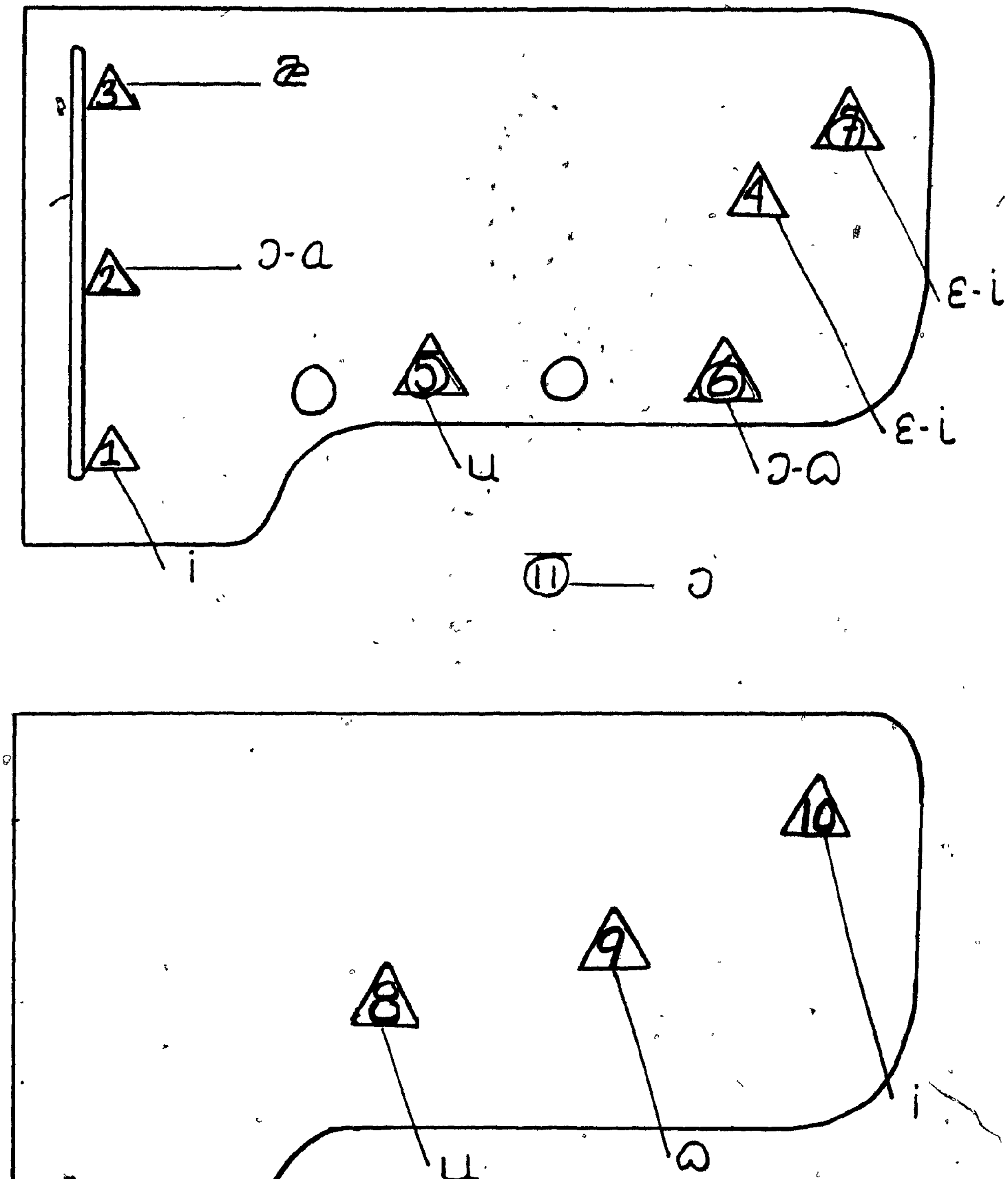


Figure 7 PIANO

Although somewhat «harsh», this timbre produced more low-end energy (up to the sixth harmonic), a main feature of the back-vowel group (u).

A second collection of pickups placed near the hammers, produced a wide range of tonal possibilities. Commencing with the treble end, the spectrum for pickup △1, situated opposite the D^2 strong (1.17KHz.), showed weak low energy up to the twelfth harmonic (1.80KHz.), and a large peak at the fifteenth harmonic (2.25KHz.) The resulting «sharp» or «percussive» quality corresponded with the front vowel (i).

The second pickup in this group, placement △2, was situated at the mid-region of the keyboard near the note F (349Hz.). The recorded timbre was perceived as «trebly» with a «thin bass» and categorized in the back-vowel group (ɔ-ɑ). The spectrum showed a weak fundamental and second harmonic (400Hz.) and an emphasis of mid-frequency harmonics (i.e., from the fifth (800Hz) to thirteenth (1.95KHz.)).

The third pickup, placement △3, produced an «open» and «clear» front-vowel sound (æ). In addition, emphasis of the lowest harmonics contributed to a «full-bass» sound. With the exception of a peak at the eighth harmonic (1.2KHz.), high-frequency energy was attenuated above the twelfth harmonic (1.80KHz.).

To complete the investigation of the top soundboard, a pickup was situated on the middle of the bass bar.[14] Due to large peaks at 2.40KHz. and 3.15KHz., the tone exhibited a «sharp» quality not found in previous placements.

A boost in the 1.5KHz.-1.8KHz. range contributed to «bright» «nasal» quality, which was categorized within the front-vowel group (ɛ-i).

The next investigation was of the timbres produced by contacts on the underside of the soundboard. A total of three pickups were arranged on the treble bar from the «head» to the «tail» of the instrument (placements △8, △9, and △10). Results indicated a «bright» quality towards the «tail».

There were a number of marked tonal differences between this and previous pickup arrangements. For example, placement △8 was situated near the curve of the harp. In this position, the resultant spectrum was devoid of exaggerated peaking in the higher-frequency region. The most significant peaks existed at the fundamental (150Hz.) and second harmonic (300Hz.). The combination of these features produced a «dull» or «muffled» tone that was categorized in the back-vowel group (u). (Compare this description with the similarly positioned pickup, placement △5).

Another pickup was placed in the middle of the soundboard, as recommended by the manufacturer of F.R.A.P.[15] (placement △9). Unlike placement △6, also situated in the sound port, this position yielded a «full», «deep» bass sound categorized within the back-vowel (ɷ) group. The frequency envelope revealed strong low harmonics with peaks at the fifteenth (2.25KHz.) and sixteenth (2.40KHz.) harmonics.

The «brightest» timbre was recorded by a pickup situated at placement △10. Compared with other placements, this spectrum showed an overall increase in level for harmonics within the 3.0KHz.-5.0KHz. band. Strong peaks were observed at 300Hz. and 3.15KHz. The formant structure of this «bright», «clear» tone was placed within the front-vowel category (i).

An overall lack of energy beyond the sixteenth harmonic (2.4KHz.) contributed to a «dull», «bassy» quality in the sound produced by the microphone (placement △11). Energy was concentrated within the first six harmonics (i.e., up to 850Hz.), with the most significant peaks occuring at the second (300H«.) and fourth (550Hz.) harmonics. The timbre was categorized in the back-vowel (ə) group.

TIME DOMAIN ANALYSIS

The attack duration of the piano was 10% shorter than that of the violin. In the low end, the microphone exhibited the slowest transient times of all the pickups tested, while higher harmonics (above the fourth harmonic) were generally equal in duration.

The analysis demonstrated far greater waveform instability for the piano than for instruments in the bowed-string group. Within the first 100mSec., the lower harmonics were fairly stable, especially at the fourth harmonic (550Hz.).

The sound-port pickups (△5 , △6 , △7) displayed quick transient times (average 69.1mSec.). Overshoot occured at the second and fourth harmonics (300Hz. and 550Hz., respectively). The fourth and fifth harmonics proved to be the most stable components in this tone (550Hz., and 700Hz.)

The «ringing» quality associated with placement △5 was explained by the great amplitude of the high harmonics around 3.0KHz. (possibly due to a resonance in the pickup (Chapter 2)). In addition, time analysis of the higher components exhibited a pseudo steady-state of 350mSec. duration after which a more stable lower level was reached. In this placement, as in others of this group, the lower harmonics were quite stable.

Pickups arranged near the hammers (△1 , △2 , △3) displayed a diversity in waveshape characteristics. Generally, the fifth and sixth harmonics were quite unstable (700Hz. and 850Hz.). In the case of the «bright» placment △1 , there was considerable instability for most of the harmonics beyond 250Hz. In contrast, «darker» placements, △2 and △3 , showed less overshoot (550Hz. and 400Hz.-550Hz. respectively).

Persistent instability of the waveform was typical of many of the «bright» or «strident» timbres analysed. For example, in the analyses of placement △4 (ɛ-i) and placement △10 (i) both contained a large overshoot at the second and third harmonic (300Hz. and 400Hz., respectively). There was also an increase in waveform instability past the sixth harmonic (850Hz.).

Analysis of the «dull» or «muted» tone produced at placement △8 showed considerable overshoot for the second and third harmonics along with a very slow-developing fundamental. After 0.5sec., the fundamental dominated the spectrum, thereby masking the higher harmonics (above 550Hz.).

Analysis showed that during the initial 200mSec. of the waveform produced at placement △9 (ɑ), the fifth harmonic (700Hz.) dominated the spectrum. After this period, the fundamental which was the weakest component, gained amplitude and emerged as one of the strongest components.

The tone produced by the microphone emphasized the lowest harmonics. The attack durations for these partials were longer than those found for the contact pickups. An especially pronounced overshoot occured at the second harmonic (300Hz.).

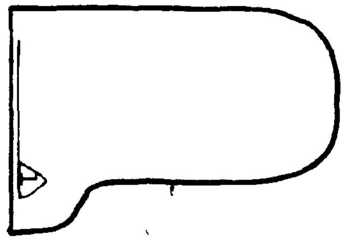
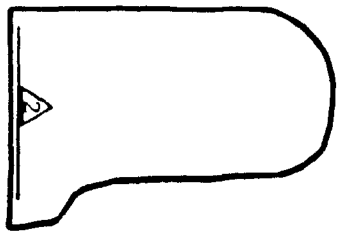
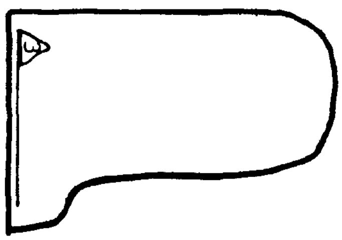
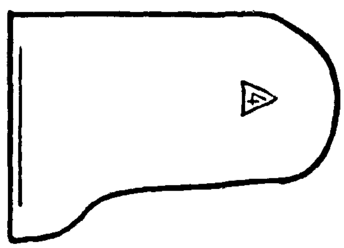
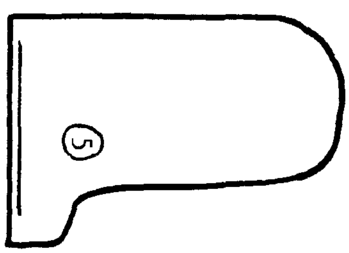
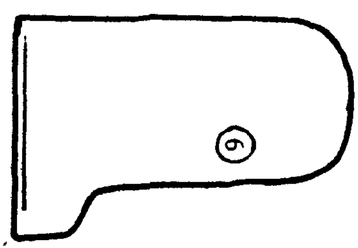
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	ɪ	strident / thin bass	-weak fundamental -peaks at 300, 2.25KHz. -trough between 400-1.0KHz -trans.instabllity-250-800 - " overshoot-550Hz.
	ɔ - ɑ	trebly / thin / weak bass	-weak fundamental -peaks at 400Hz.;700Hz.; 1.65KHz.; 2.85KHz. -troughs at 300Hz.;1.0KHz. -trans.instability-700 - 800Hz. -trans.overshoot-550Hz.
	æ	clear / open	-strong fundamental -peaks at 400Hz.;1.2KHz. -trough at 300Hz. -most energy below 2.5KHz. -trans.instability-700 -trans.overshoot-400-550Hz
	ɛ - ɪ	very bright / nasal	-weak fundamental -peaks at 400Hz.;2.40KHz.; 3.15KHz. -troughs at 300Hz.;1.0KHz. -trans.overshoot-300Hz.- 400Hz.
	u	harsh / extreme ringing	-strong fundamental -peaks at 700Hz.;2.45KHz. -boost between 300-400Hz. -troughs at 550, 1.0KHz. -trans.overshoot-300 -400
	ɔ - ɑ	thin bass & nasal	-strong fundamental -peaks at 300Hz.; 550Hz.; 2.15KHz. -trough between 850Hz. - 1.15KHz. -trans.overshoot-300Hz.

Table V

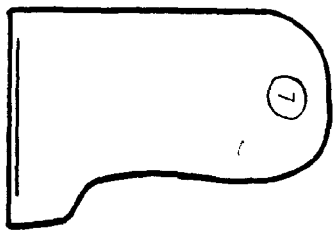
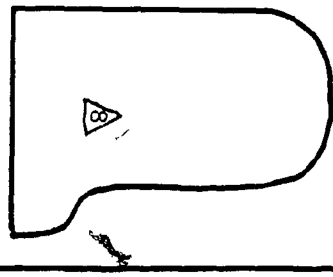
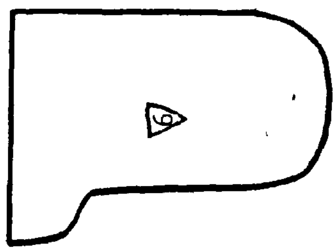
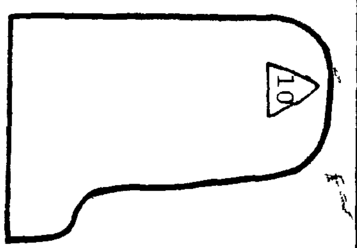
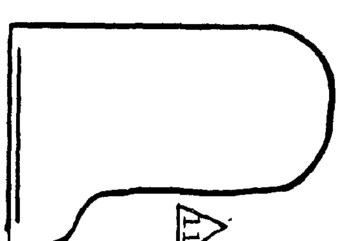
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	ɛ - ɩ	bright	-strong fundamental -peaks at 1.0KHz.; 2.25KHz -boost between 980-2.7KHz. -trans.overshoot- 300Hz.; 550Hz.
	u	muted / muffled/ dull	-weak fundamental -peaks at 300Hz.; 550Hz. -absence of high frequency harmonics -trans.overshoot- 300Hz.
	ɷ	full bass sound/ muted high end	-strong fundamental -peaks at 300Hz.; 400Hz, -boost between 2.25-2.4KHz -little energy beyond 2.55 -trans.overshoot- 300Hz.
	ɪ	bright / clear high end	-strong fundamental -peaks at 300Hz.;1.4KHz. -3.15KHz. -trough between 850-1.1K -trans.overshoot-300Hz.
	ɔ	bassy / muted highs	-strong fundamental -peaks at 300Hz.; 550Hz.; 2.46KHz. -trans.overshoot- 300Hz.

Table V (a)

GUITAR

FREQUENCY

In this study, ten pickups were placed as illustrated in Figure 8. Two main areas of the front plate were investigated: a) around the bridge and; b) on the upper portion of the body. After preliminary investigation, a single pickup position was selected to best represent the back plate. For comparision, a Neumann U87 microphone (omni) was placed one meter from the performer.

The instrument was a high-quality nylon-stringed acoustic guitar. The performer was asked to pluck the note G#, (utilizing his nail), sustaining the note for approximately three seconds.

Five pickups were arranged near the bridge. Manufacturers of the F.R.A.P. suggest a placement slightly off to the right of the bridge,[16] similar to placement △4. Analysis of the spectrum produced at this point revealed a strong fundamental and a prominent peak at 250Hz. A lack of high-harmonic information contributed to the «bassy», or «dull» quality. The timbre was compared with the high-back vowel (u) group.

Placement △5, situated on the bass side of the bridge produced a «weaker» bass than placement △4. Spectrum analysis of placement △5 uncovered a weak fundamental with peaks at 250Hz., and a boost between 500Hz.-600Hz. This placement, categorized in the back-vowel (ɔ) group, was described as «bassy» with a «muted high end».

Although the placement of pickups on the bridge itself is not usually recommended (see Cello Section), listeners described the timbre produced at placement △1 as «full» and «open». The spectrum of the tone contained strong peaks at 650Hz. and 1.0KHz., with a boost of the region 250Hz.-350Hz. The tone was characterized within the front-vowel (æ) group.

Placement △3 represented a position behind the bridge near the lower strings. Analysis of the tone revealed a strong fundamental with prominent peaks at 250Hz. and between 500Hz.-600Hz. The higher harmonics, (until 2.5KHz.) were strong in comparison with either placements △4 or △1 . The formant structure of this tone (comparable to the (æ) vowel type) was described as «solid» or «full».

A pickup placed directly behind the treble area of the bridge produced the «brightest» timbre. In this position, placement △2 yielded a strong fundamental with peaks at 250Hz. and 850Hz. Corresponding with the front-vowel group (æ - ɛ), the timbre was described as «bright» but with a «weak-low end».

A second group of pickups arranged on the upper area revealed greater tonal differences. For example, a «bassy» and «muted» timbre was recorded by a pickup at placement △9 . Categorized within the back-vowel (ɔ) group, the spectrum contained a strong fundamental and a broad peak between 600Hz.-750Hz.

Another pickup position to the left of the neck (placement △7), presented a «bright», «edgy» tone. Compared to the previous recorded timbre, the spectrum showed greater amplitudes in the 650Hz.-900Hz. range, corresponding to the high-vowel group (æ - ɛ).

The «brightest» sounds emanated from pickups situated near the port, placement △6 , or by the neck, placement △8 . Analysis of the former

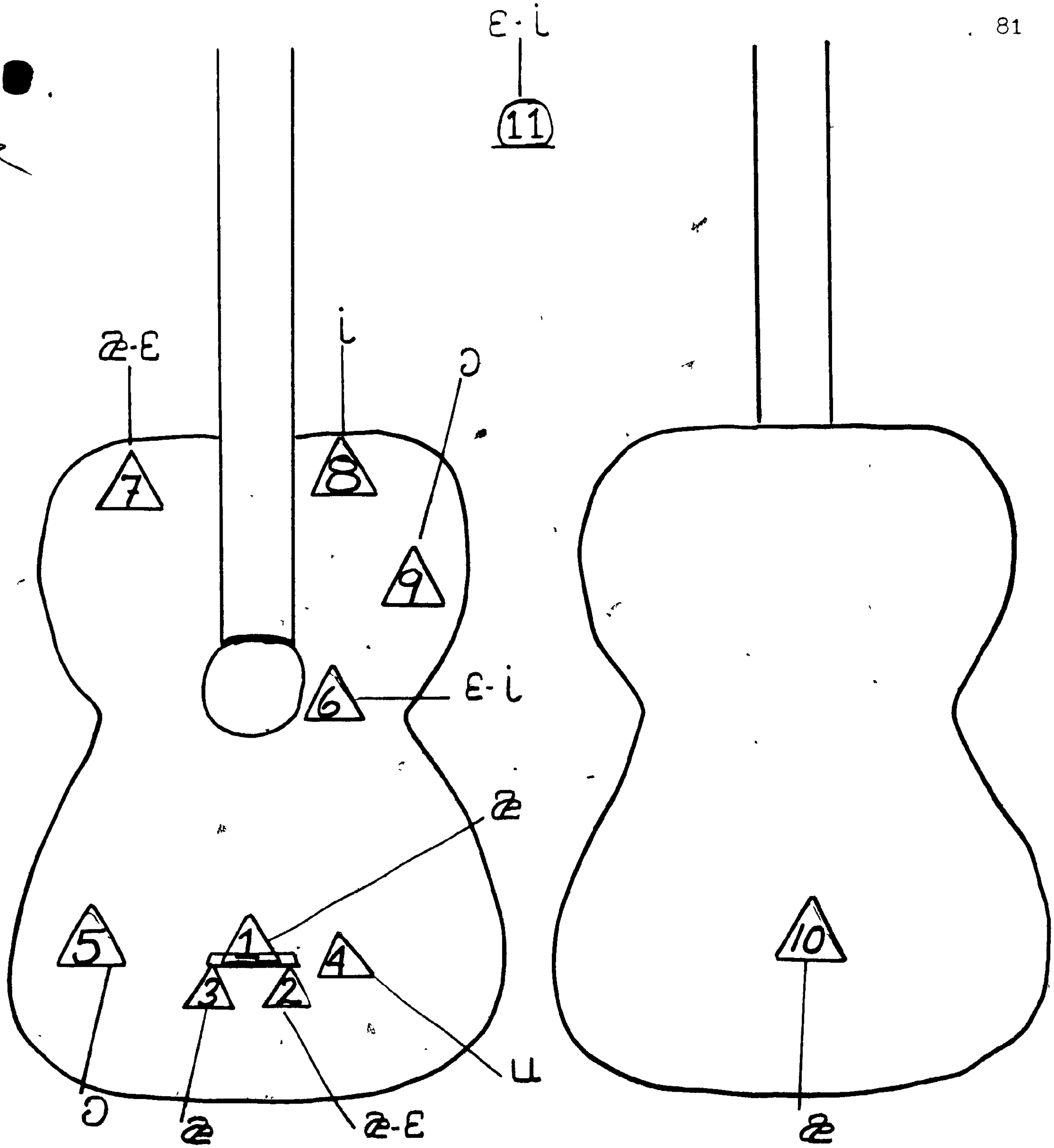


Figure 8 GUITAR

tone disclosed a weak fundamental followed by strong harmonics at 350Hz., 500Hz., and at 1.1KHz. The timbre was considered to have had a «medium-bright» quality, and a «weak-low end». The formant envelope of this tone related to the front-vowel group (ɛ-i).

From the latter placement a «bright» yet «thin» tone was produced. Peaks occured at 250Hz., 750Hz., and at 1.1KHz., forming a resonant structure comparable to the front-vowel group (i). A substantial trough from 350Hz.-650Hz. weakened the bass.

A pickup positioned on the back plate, placement △10, produced a «solid» and «open» sound, corresponding to the low-front vowel (æ). Along with a strong fundamental, analysis uncovered peaks at 250Hz., 600Hz., and 905Hz.

Although listeners described the tone produced by the microphone as «duller» than those of the pickups, it was, nevertheless, considered «clear». Analysis of the recorded timbre disclosed a strong fundamental along with peaks at 150Hz. and 600Hz. In addition, higher harmonics were attenuated more so than in tones produced by the pickups.

TIME DOMAIN ANALYSIS

The analysis of the guitar's attack duration revealed an average time of 90.5mSec. Throughout this investigation, the most notable difference from the piano and other stringed instruments was the large variation in amplitude at the second harmonic (250Hz.). This variation was greatest during the first 0.5sec of the sound. Because the level was so large and consistent throughout these analyses, it remains an identifying acoustical feature of the guitar sound in this register.

Placements yielding bright timbres, such as placement 8 (i) demonstrated instability at the third and fourth harmonics (350Hz., 650Hz.) Harmonics in the 650Hz.-1.1KHz. range (fourth to seventh) achieved the greatest level within the first 60mSec., while the lower harmonics, especially the second, developed more slowly.

In a number of the «brighter» bridge placements analysed, the highest harmonics decayed most rapidly, after 200mSec. In the analysis of placement 2, the proximity of the pickup to the treble area of the bridge was responsible for great amplitude levels in the high harmonics, especially during the transient period.

In contradistinction to the pickups, the tone produced by the microphone was devoid of large amplitude variations in the higher harmonics. In the lowest partials, overshoot was prevalent, notably at the sixth (600Hz.). Also, the fundamental and second harmonic demonstrated large amplitude variations.

Analysis of the wave form produced at the back-plate placement, 10, did not uncover major differences with front-plate analyses. However, the absence of a large overshoot at the second harmonic (250Hz.), accompanied with a more stable fundamental was noticed. In comparison with front plate pickups, placement 10 exhibited fewer amplitude changes during the initial 100mSec. of the sound.

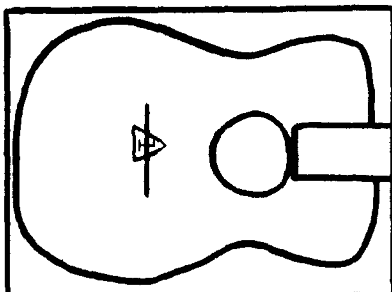
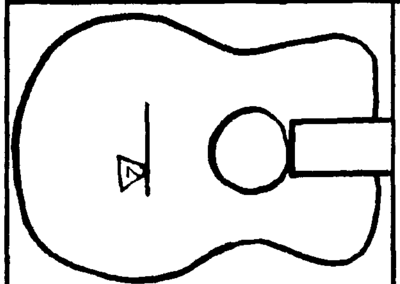
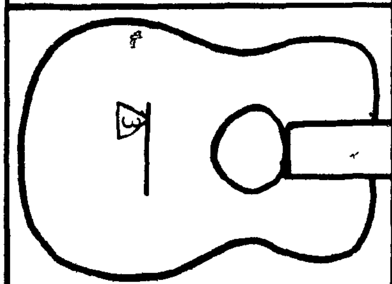
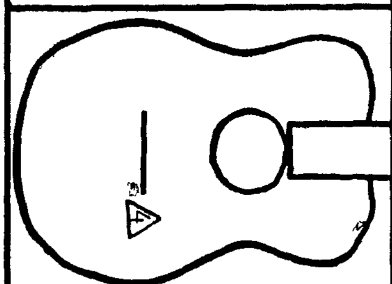
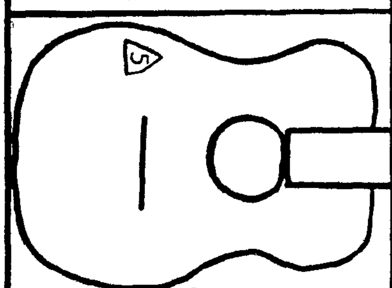
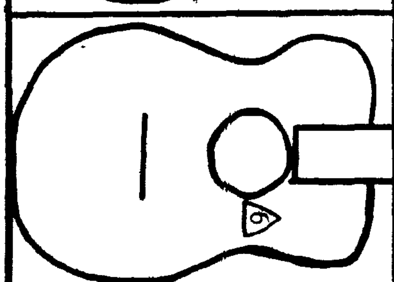
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	æ	full bass / open	-weak fundamental -peaks at 650Hz.; 1.0KHz. -boost between 250-350Hz. -trough at 475Hz. -trans.instability-650Hz.
	æ - ɛ	bright / weak low end	-strong fundamental -peaks at 250Hz.; 850Hz. -troughs at 400Hz.; 750Hz. -trans.instability-350 - 700Hz. -trans.overshoot-100-250Hz
	æ	solid mid and low end	-strong fundamental -peaks at 250Hz. -boost between 500-600Hz. -troughs at 450Hz.;1.0KHz. -trans.overshoot-250Hz.
	u	bassy / dull	-strong fundamental -peaks at 250Hz.;350Hz.; 1.0KHz. -lack of high harmonics -trans.instability-600-900HZ. -trans.overshoot-350Hz.
	ɔ	bassy / muted high end	-weak fundamental -peaks at 250Hz. -boost between 500-600Hz. -trough at 200Hz.;450Hz. -trans.instability-100Hz.; 900Hz. -trans.overshoot-500Hz.
	ɛ - ɩ	med-bright / weak low end	-weak fundamental -peaks at 350Hz.;500Hz.; 1.1KHz. -trough at 870Hz. -trans.instability-950Hz.

Table VI

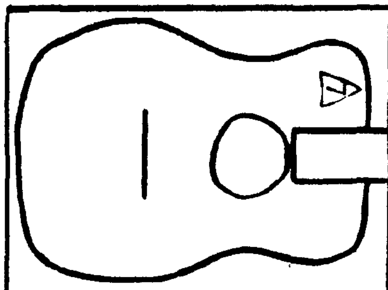
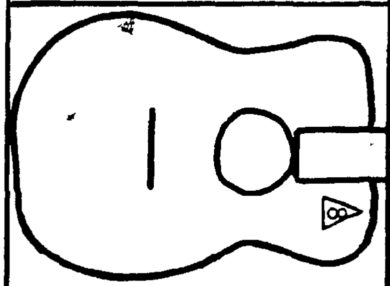
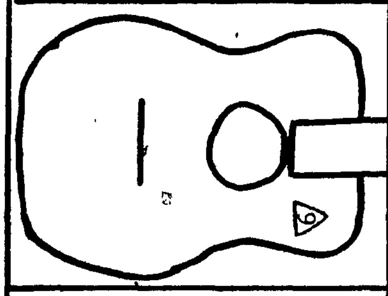
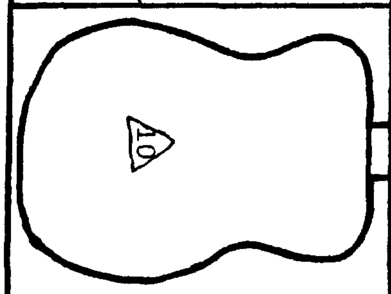
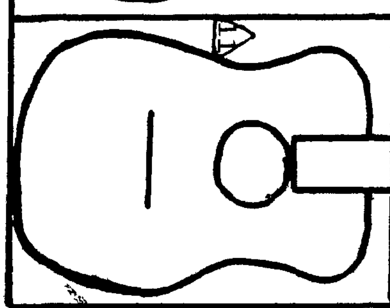
	VOWEL IDENTITY	TIMBRE DESCRIPTION	SPECTRAL FEATURES
	æ - ɛ	bright / mid-freq edge	-strong fundamental -peaks at 250Hz. -boost between 650-900Hz. -trough at 500Hz. -trans.instability-650 - 900Hz. -trans.overshoot- 650-900 Hz.
	ɪ	thin /constricted	-strong fundamental -peaks at 250Hz.;1.1KHz. -boost between 750-1.45KHz -trough at 500Hz. -trans.instability-650Hz.
	ɔ	bassy / muted high end	-strong fundamental -peaks at 250Hz.;600Hz.; 1.1KHz. -deep trough at 200Hz. -trans.instability-850Hz. -trans.overshoot-600Hz.
	æ	solid low end	-strong fundamental -peaks at 250Hz.;600Hz.; 905Hz. -trough at 450Hz. -trans.instability-150, 350Hz. -trans.overshoot-100-600
	ɛ - ɪ	clear high end	-strong fundamental -peaks at 150Hz.;600Hz. -trough at 750Hz. -trans.instability-250Hz. -trans.overshoot-150Hz.

Table VI (a)

CHAPTER 6

CONCLUSION: A COMBINATIVE MICROPHONE TECHNIQUE

The experiments reported in the last Chapter dealt with the tonal affect created by individual contact and microphone placements on a number of acoustical instruments. The discussion in this Chapter will seek to examine a combinative approach for sound pickup that takes advantage of the timbral flexibility provided by both types of transducers. The fundamental principles of the combinative method are consistent with multi-microphone techniques proposed by Woszczyk and Bartlett.[1] However, whereas timbral colorations or modifications produced by close-microphone air-transducer arrangements are dependent upon the changing directional patterns projected by a source within the near and far fields,[2] the combinative technique balances the «sharp» transient detail of the instrument's vibrational energy with the «rich» harmonic information contained in the reverberant environment. Application of this technique in practical recording situations shows that specific combinative arrangements provide a naturally effective method of shaping an instrument's timbre.

NATURAL EQUALIZATION

The concept of natural equalization which refers to accumulation of spectral information solely by means of microphone placement, underlies all multi-microphone techniques. In other words, an instument's timbre can be reconstructed from selected transducers arranged around the source. Ideally, an assemblage of the spectra radiated by the instrument in the «near» and «far» fields will provide a complete or natural timbral balance.[3]

In reality, however, non-linear distortions, inherent in the design of most transducers, limit the effectiveness of any micropnone system. For example, pressure-gradient transducers increase bass frequency output with proximity to the acoustical source. A more distant placement reduces the proximity effect but increases unwanted leakage. Moreover, dynamic gradient microphones are subject to mechanical and wind interferences, due to their low-frequency tuned diaphragm design.[3] Of course, the acoustical characteristics of the recording environment also contribute to spectral imbalances, when microphones are used.

Since the frequency response of a typical audio pickup is largely dependent upon mounting procedures (Chapter 2), the pickup is considered less reliable than air transducers. However, it is still preferred in situations where optimum isolation and timbral selectivity are desired. In addition, transient information, often lost in distant microphone arrangements, is effectively captured by the pickup, resulting in added tonal «clarity» and «brilliance».

SELECTED EXAMPLES OF THE COMBINATIVE TECHNIQUE

BOWED STRINGS

In the investigation reported here, specific contact and air transducers are combinatively arranged. Focus in this section is on the type of selective equalization provided by the combinative arrangements. In order to distinguish the spectral contributions of each transducer, a series of graphs are given in which the pickup spectra is subtracted from the microphone spectrum.[4]

Figure 9 illustrates a combinative arrangement which enhances the upper mid-frequency of the violin. The accompanying graph shows an increased level for the bass register (maximum boost of 4dB. at 200Hz.) along with a broad peak centered around 1.75KHz. The substantial energy within the 400Hz.-500Hz. area and in the 1.0KHz.-2.0KHz. produces an «open» if somewhat «nasal» (æ) sound.

A combination which produces a broader high-end emphasis is illustrated in the graph next to Figure 10. This setup features three equalization points centered around 950Hz., 2.0KHz., and 5KHz. (maximum boost of 12dB). Compared to the previous setup, there is less accentuation in the 400Hz.-800Hz. region. A «brighter» yet «thin» (ɔ) quality is associated with the resultant timbre.

The arrangement shown in Figure 11 is especially effective in reproducing a «deep», «clear» low end. Emphasis in the upper portions of the spectrum (maximum boost at 950Hz. and 5KHz.) is complemented with a prominent bass (maximum boost at 200Hz.) The combinative arrangement possesses a «solid» (u) quality.

Due to poor low-frequency radiation, the viola has a naturally weak bass register (Chapter 3). In many instances low-frequency energy is dissipated long before reaching the diaphragm of the microphone. On the other hand, a more effective method of obtaining low-end energy is by the use of contact pickups due to their proximity to the main resonant energy.

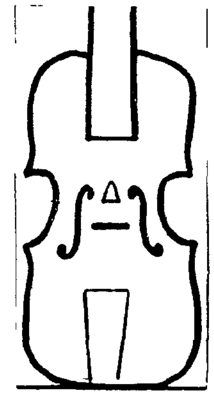
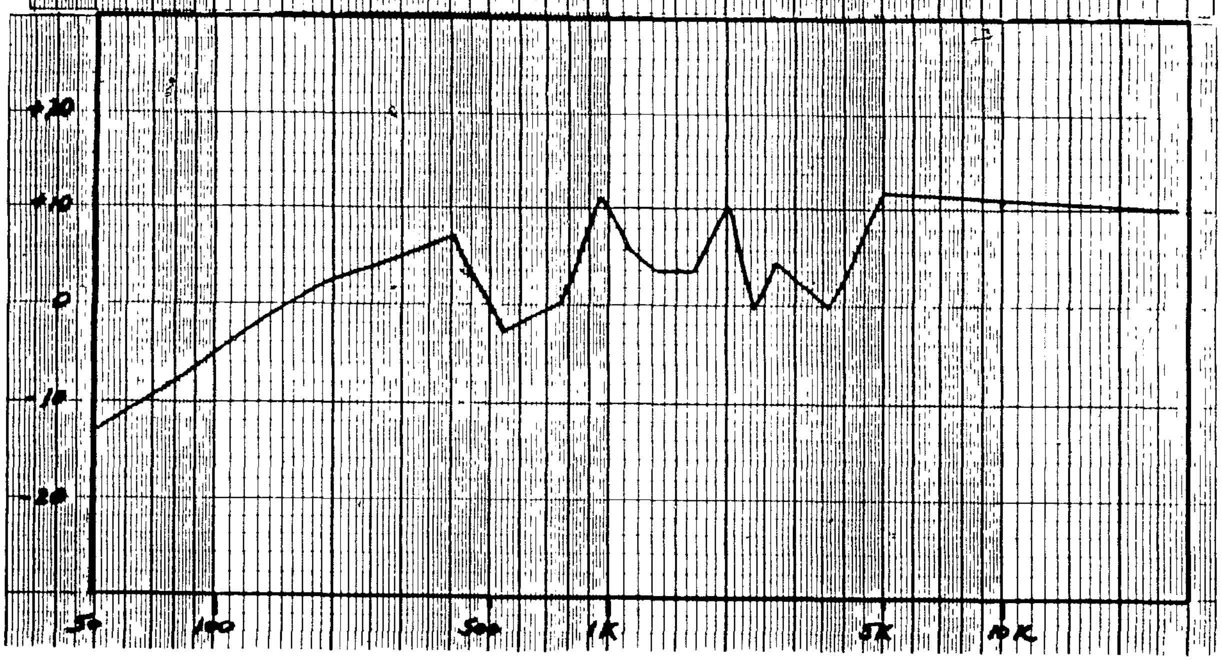


Figure 9

"open" "nasal"

"open" "nasal"



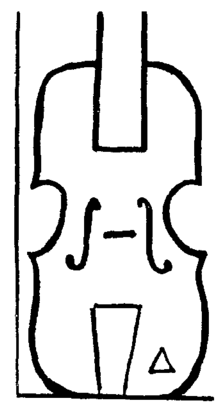


Figure 10

"bright" "thin"

"

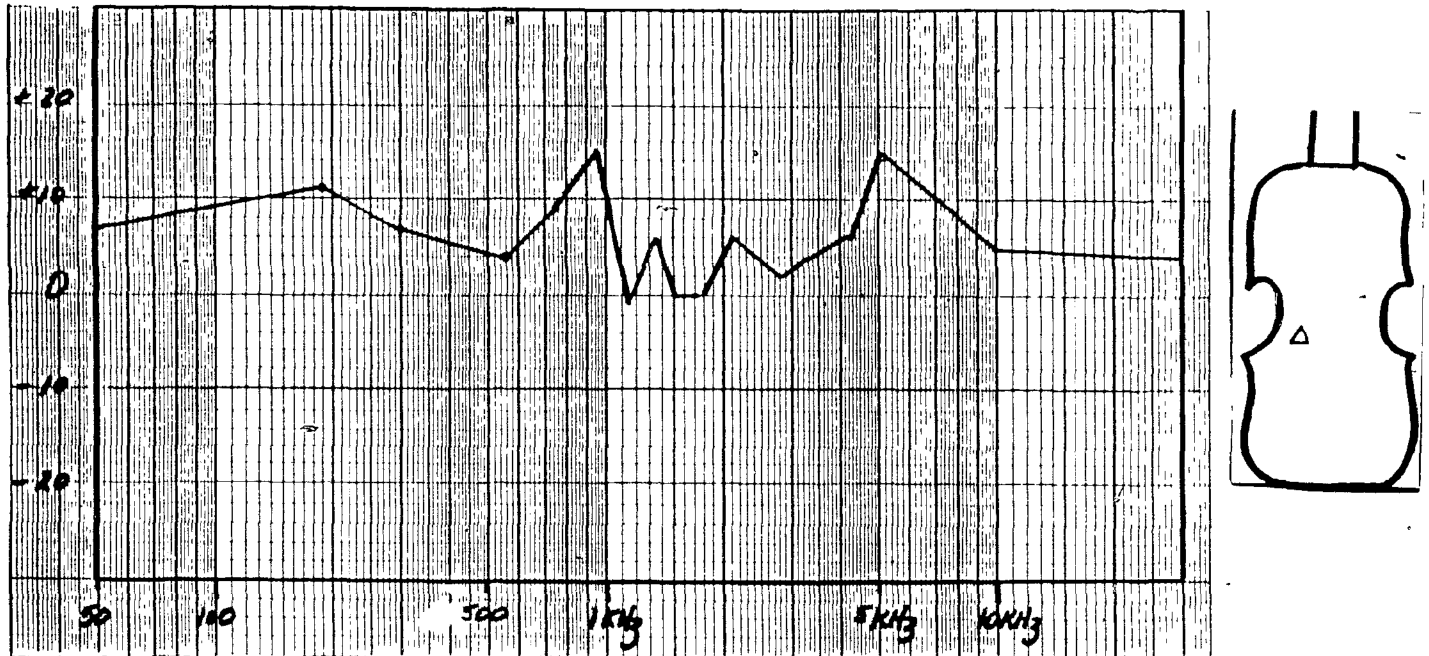


Figure 11

"deep" "clear"

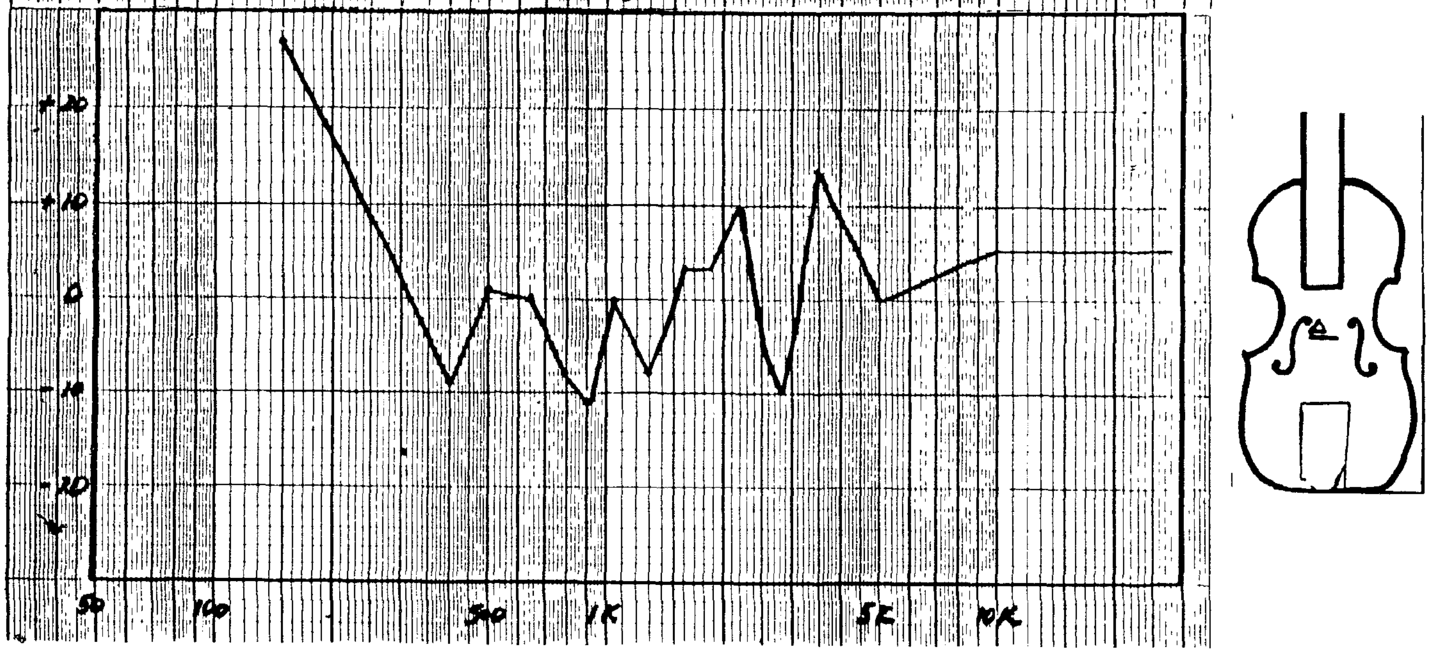


Figure 12

"well-defined bass"

Figure 12 demonstrates a setup producing an effective low-end boost. The graph illustrates a significant amplitude increase in the bass (maximum boost at 150Hz.) along with high-end enhancement (peak at 3.5KHz.). In this arrangement the microphone supplies most of the mid-frequency energy (400Hz.-3.0KHz.). The composite tonal mixture represents a «solid» and «well-defined» bass sound.

Spectral analysis of the recorded viola tone, produced by the microphone, shows a rapid attenuation of high-frequency components. Recovery of this information is achieved in the setup illustrated in Figure 13. The graph demonstrates a considerable mid and high-frequency boost (maximum peak at 2.3KHz. with a slightly smaller one at 3.4KHz.) The resultant sound possesses an «open», «trebly» quality (ɔ).

The recorded viola sound, produced by the setup depicted in Figure 14, emphasizes both ends of the tone's spectrum (maximum boost at 180Hz., with a smaller peak at 3.0KHz.) A «bright» and «open» quality (æ-ɛ) is produced.

Results from combinative transducer arrangements for the cello indicate striking advantages over a single microphone pickup. Preliminary spectral testing showed that a single microphone method often produces tonal imbalances, especially in the bass. The combinative arrangement of Figure 15 offers one solution to this problem. Emphasis around the fundamental compliments another boost at 800Hz. The tone is described as «clear» and «open» (æ-ɛ).

The setup shown in Figure 16 produces a «full», «bassy» quality (u), which helps to improve the weak low register. A boost below 200Hz. (maximum

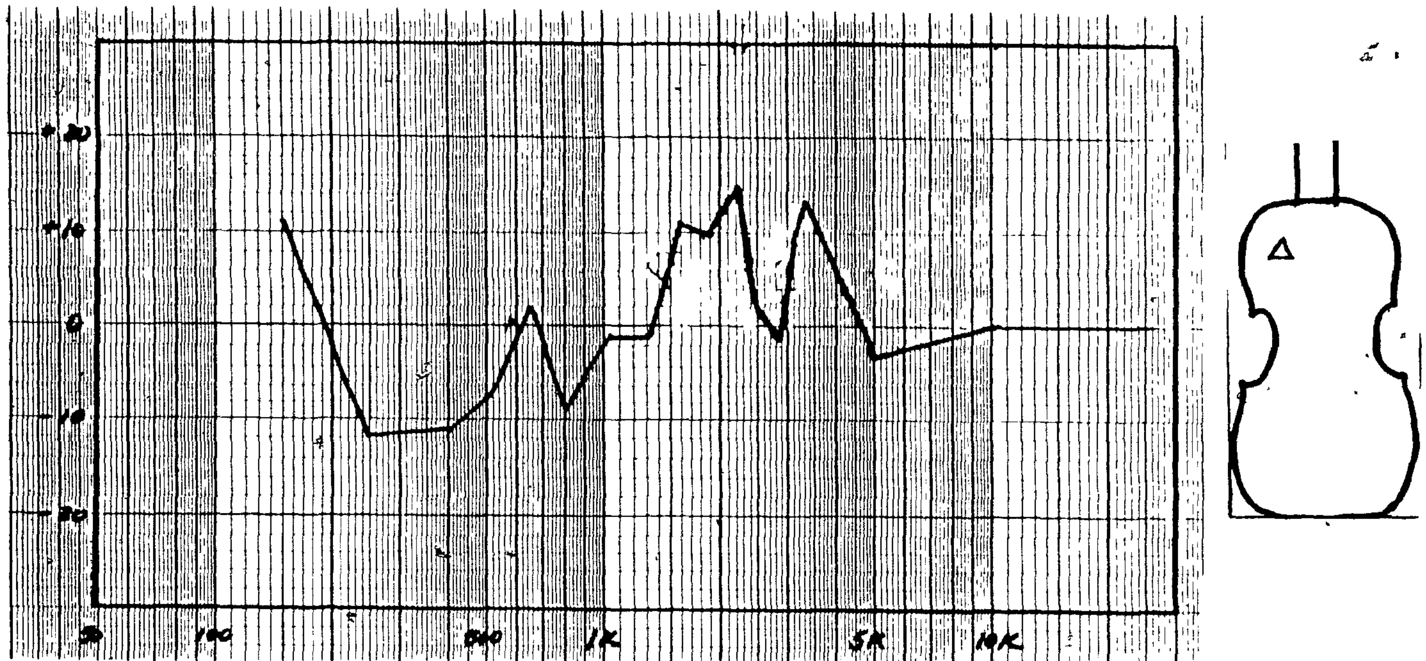


Figure 13

"open" "trebly"

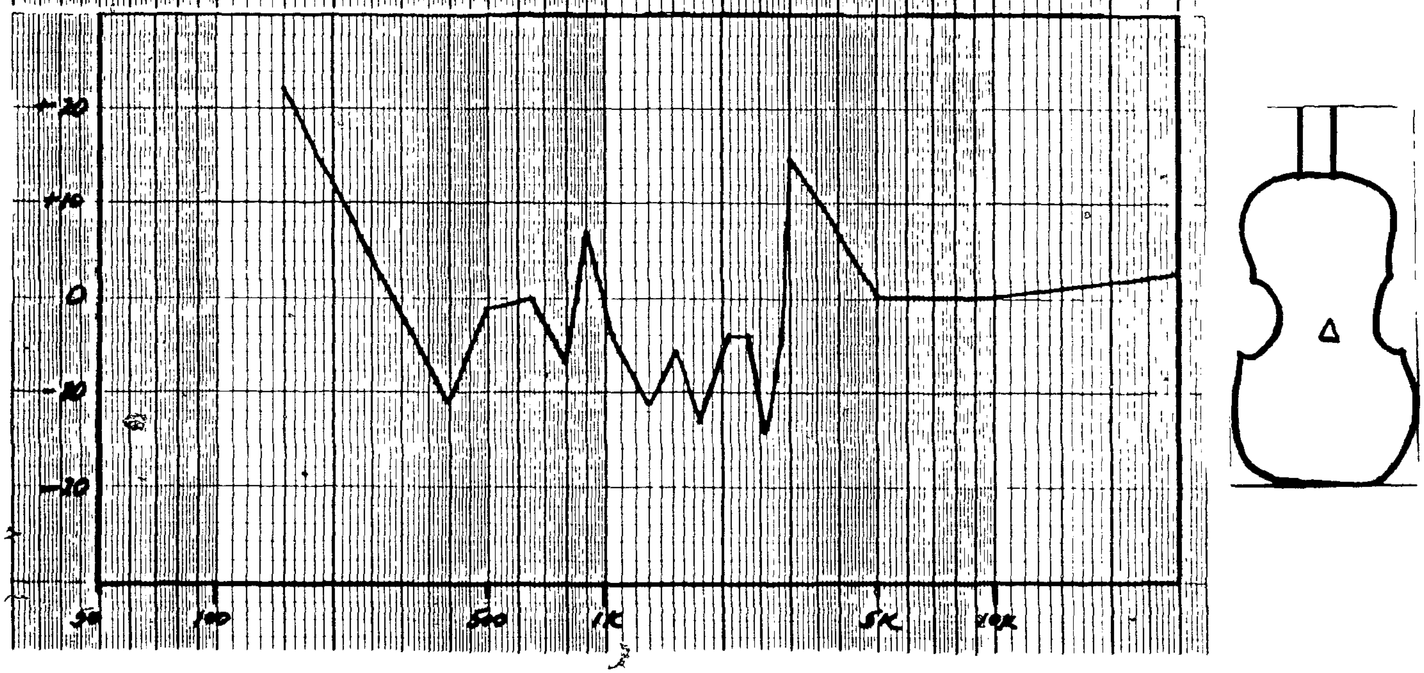


Figure 14

"open" "bright"

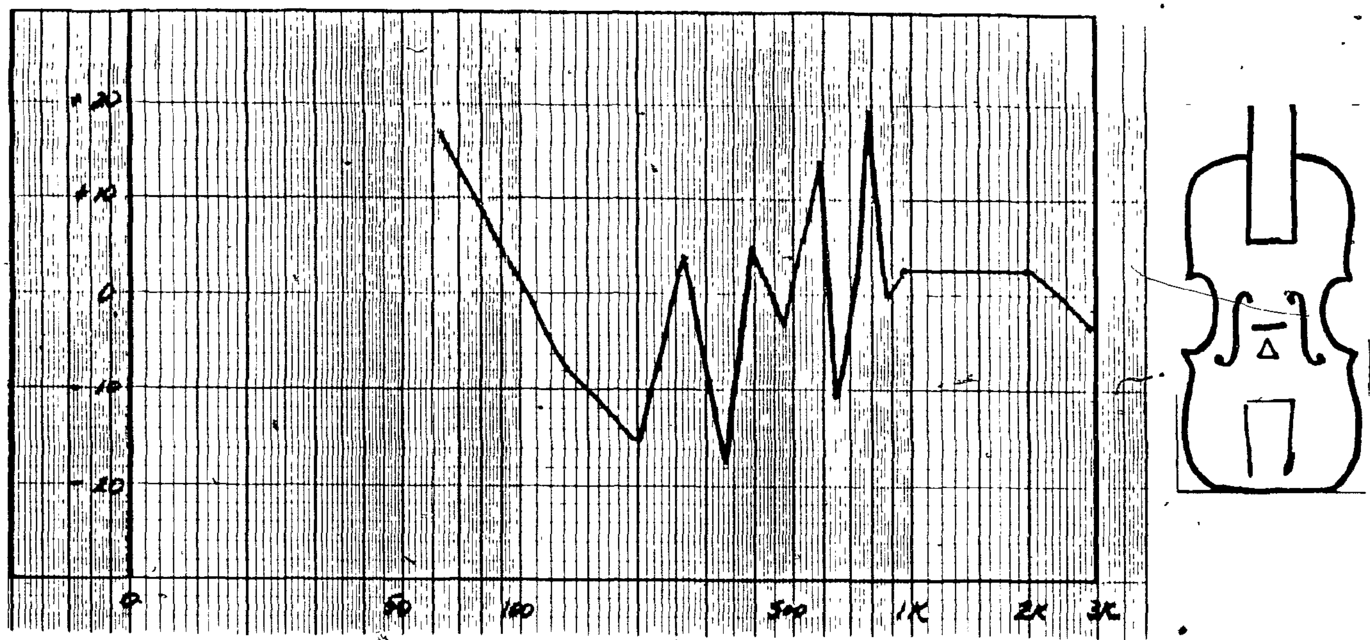


Figure 15

cello

"open" "clear"

Figure 16

"full" "bassy"

peak at 62Hz.) accompanies a smaller one at 550Hz. Components above 850Hz. are attenuated. When the cello is orchestrated as the lowest voice of an ensemble, the «deep bass» quality produced by this arrangement could be most effective.

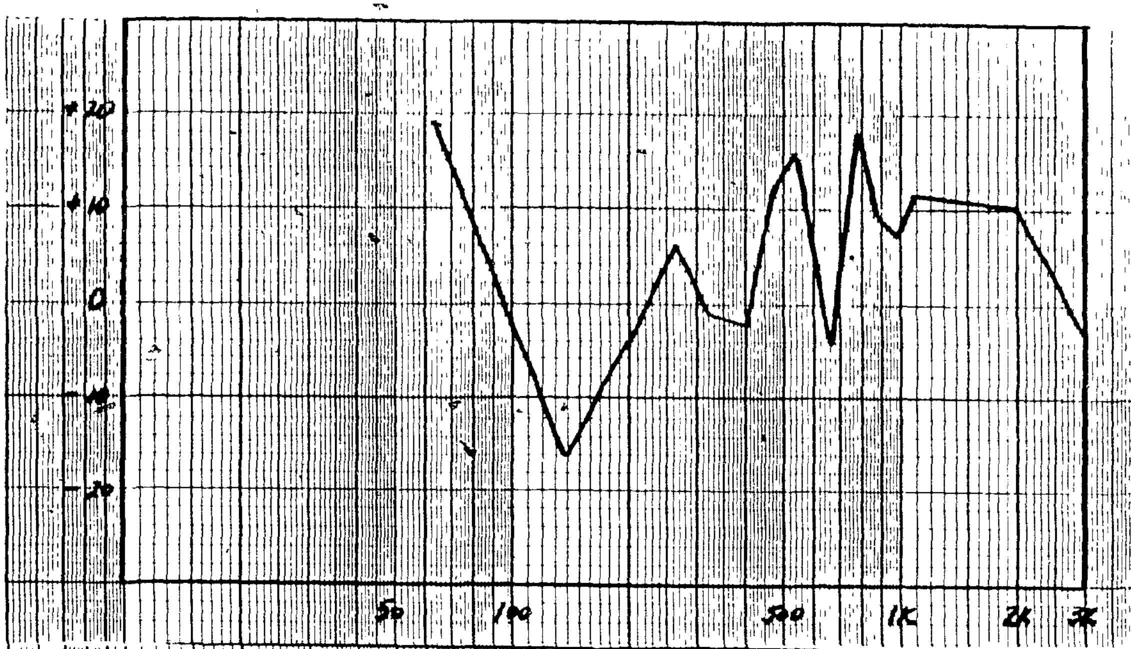
Significant improvements in the «clarity» of the cello timbre are apparent when the spectrum shows a boost above 1.0KHz. Figure 17 illustrates an arrangement which significantly increases the tonal «brilliance». The analysis demonstrates a solid fundamental complimented with a broad plateau in the high end. The resulting timbre possesses a «very bright» or «sharp» quality.

Since the double bass is unable to radiate effectively the lowest notes (Chapter 3), recorded tones in this register are usually «hollow» or «thin». For example, analysis of the solitary condenser microphone (omni) reveals that components lying between 150Hz.-300Hz. have the greatest amplitude level. Significant dips below 100Hz. and above 1.5HKz not only lessen the «solidity» of the bass, but also weaken the «clarity» of the articulation. Improvement in both areas can be achieved through combinative arrangements.

Figure 18 illustrates a setup which increases the bass and treble end, resulting in a «bright» (i) sound. The accompanying graph shows a large amplitude peak at the fundamental, with components above 500Hz., receiving emphasis (maximum peak at 550Hz.).

A «well-rounded» and «clear» sound was recorded by the placement illustrated in Figure 19. The analysis demonstrates a significant boost in the lowest end (maximum peak at 32Hz.), and a large peak at 24Hz.

Figure 20 represents an arrangement emphasizing the low end. Not as «open» as the prior example, this setup produces a «dark» (u) quality.



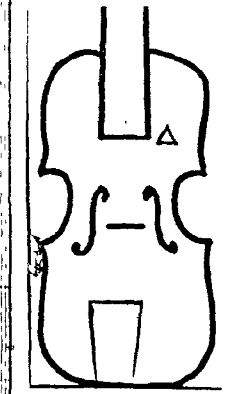


Figure 17

"sharp"

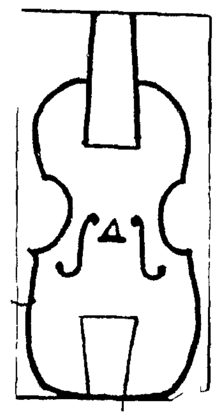


Figure 18

bass

"bright"

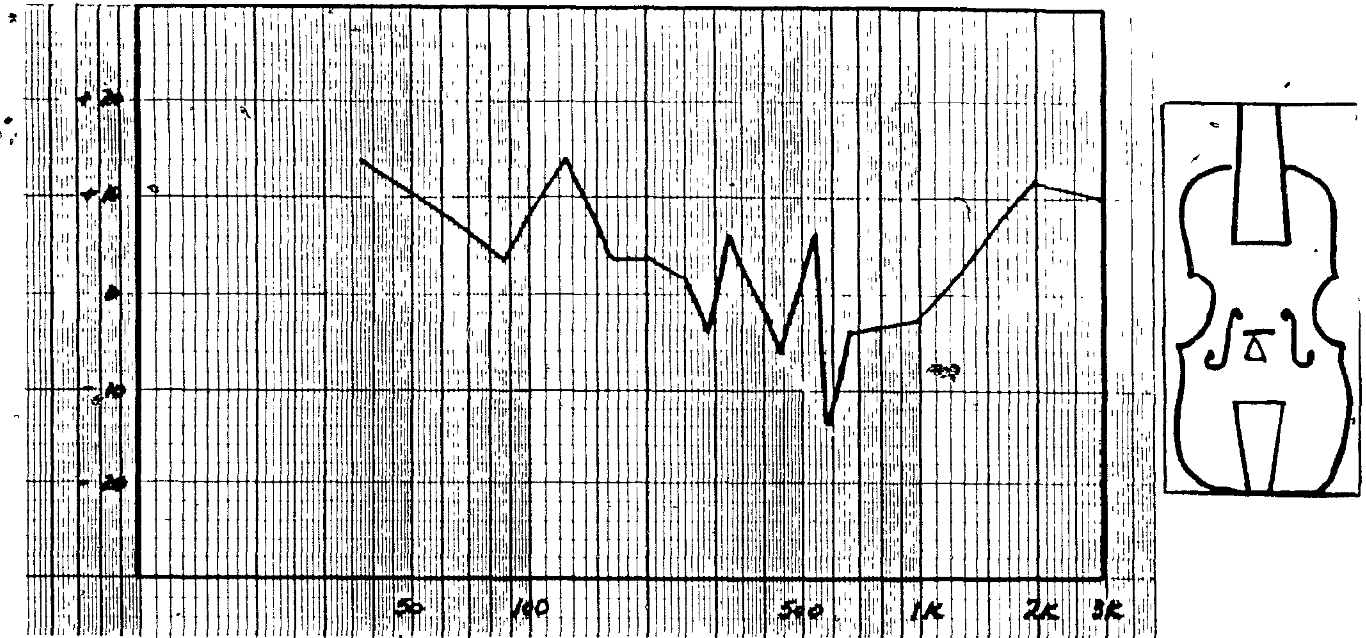


Figure 19

"well-rounded" "clear"

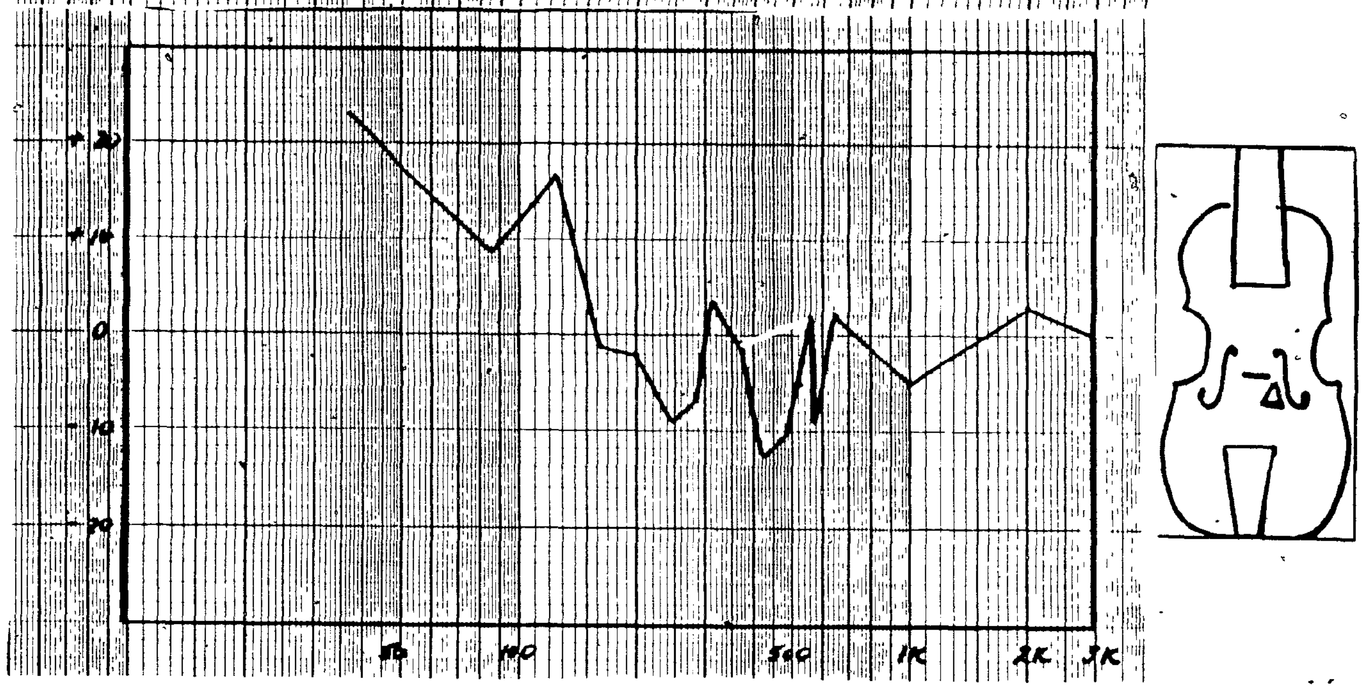


Figure 20

"dark"

PIANO

One of the problems in reproducing a «full» yet «clear» sound is that the fundamental of the piano is naturally weak in the lowest two octaves (Chapter 3). A distantly placed microphone is unable to capture the fine transient detail of the projected sound, thereby, degrading the definition in the low end. On the other hand, combinative arrangements are generally more successful in reproducing the «sharp» or «percussive» tonal quality that is often desired in «pop» or «jazz» music. Even in more «classical» situations, where a solo piano is competing against an orchestra, combinative arrangements can «clarify» the articulative features indicated in the score.

Figure 21 illustrates a combinative arrangement that enhances the mid-range portion of the spectrum (maximum boost at 1.35Hz.). A further boost at 3KHz provides «presence». Although the tone is «thin» in the bass, this setup is successful in providing an «open» and «clear» (ℰ) quality.

The combination shown in Figure 22 features an enhancement of the extreme regions of the piano spectrum. The graph illustrates a broad emphasis of the lowest register extending to 450Hz. (with a miximum boost at 150Hz.). Higher amplitudes throughout the upper-frequency regions contribute to the «bright» (ℰ- ί) timbre.

Figure 23 reveals a combinative arrangement which could be effective in situations requiring more bass emphasis. The analysis uncovers a prominence of frequencies up to 500Hz. (maximum boost at 300Hz.), with a further emphasis around 1.75KHz. Attenuation past 2.0KHz., gives a «muted» quality to the sound, providing more weight in the lower register. The resulting timbre possesses a «solid» «dark» quality (ω).

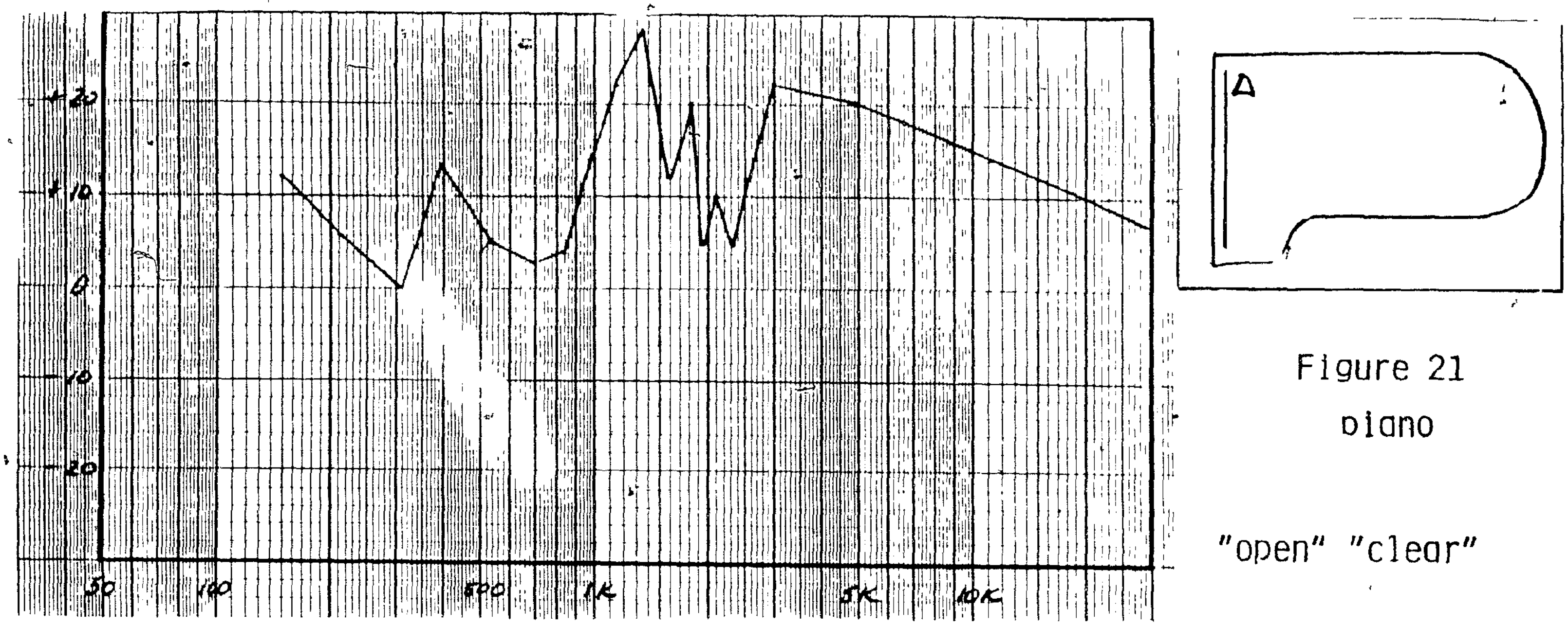


Figure 21
piano

"open" "clear"

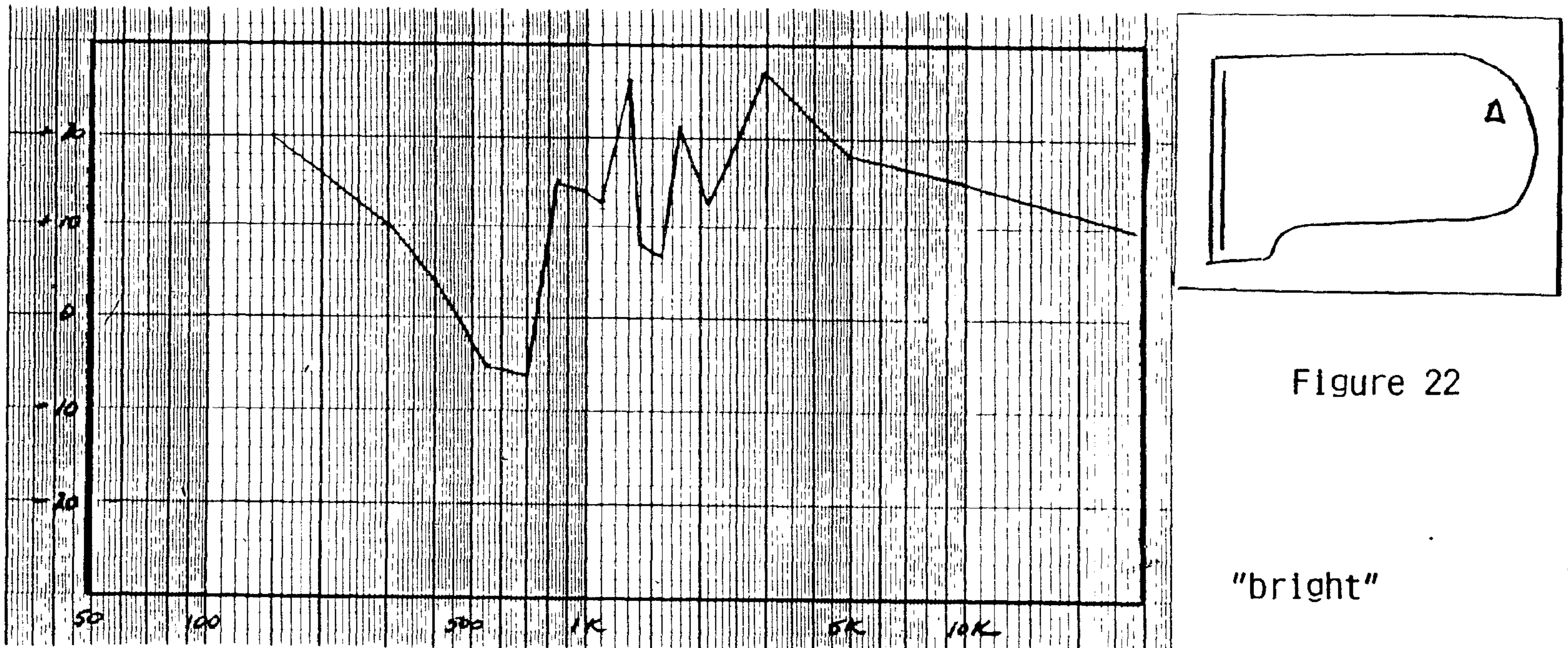


Figure 22

"bright"

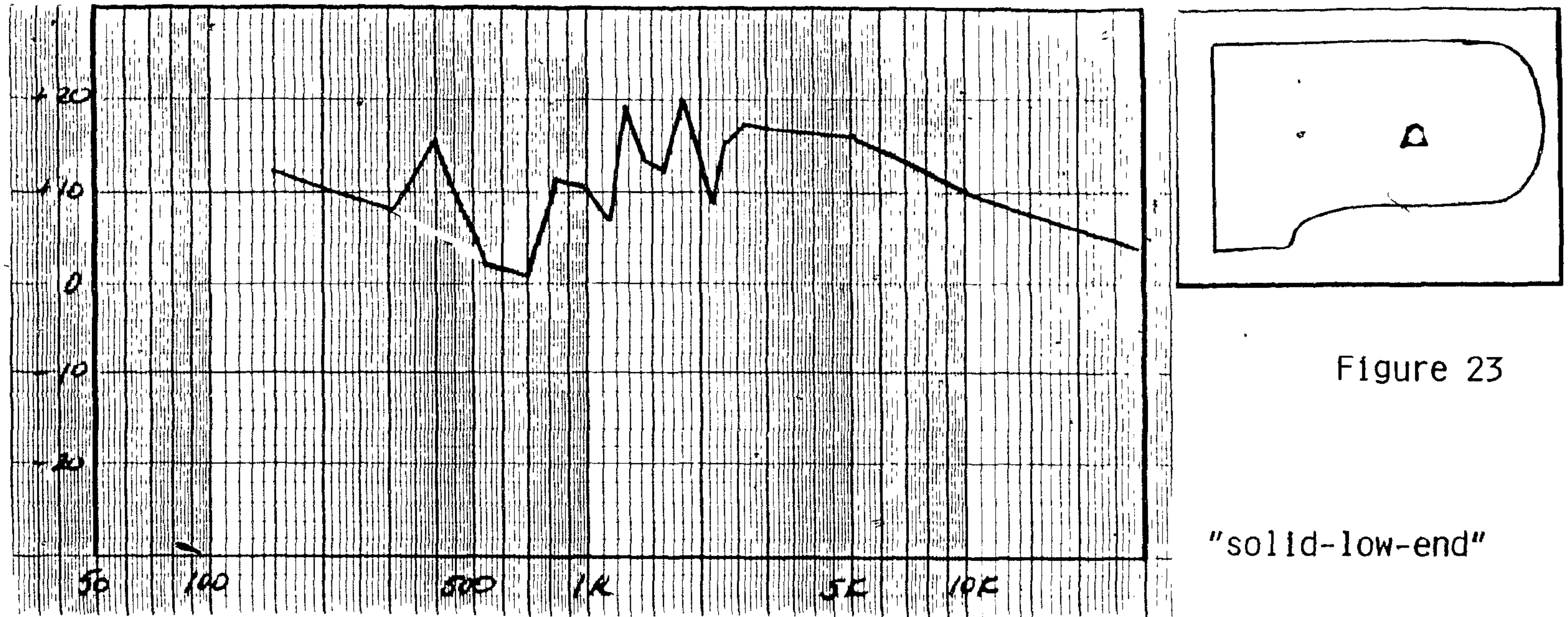


Figure 23

"solid-low-end"

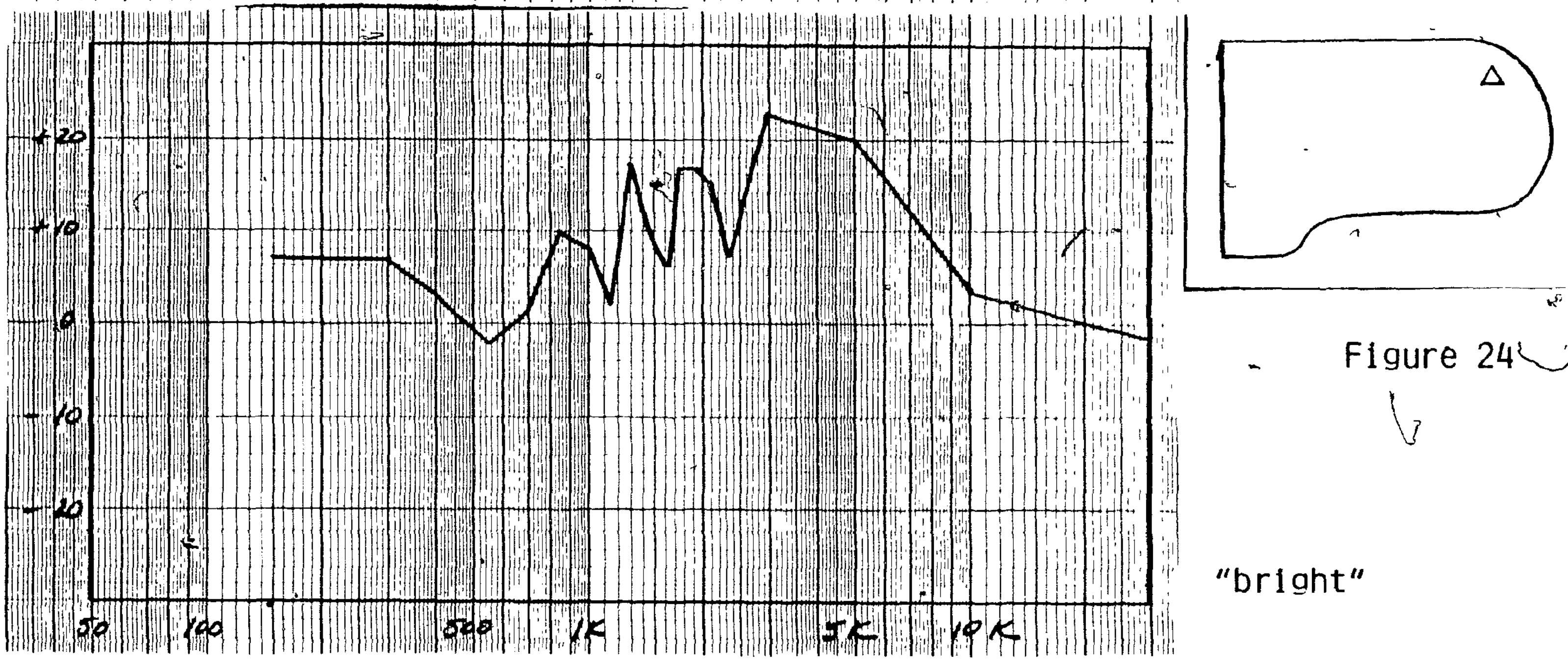


Figure 24

"bright"

In situations where a «sharp» or «percussive» tone is required, a pickup may be utilized near the hammers. The arrangement shown in Figure 24 makes use of the high-frequency energy available in this region in order to produce a «bright» (i) sound. The accompanying graph resembles a high-pass filter, with a maximum boost at 3KHz. Emphasis is therefore on the 3KHz.-7KHz. range, while low-frequency information is attenuated.

GUITAR

As the placement of an air transducer approaches the rose of an acoustic guitar, a significant bass boost is felt which may adversely affect the sound quality. Conversely, a more distant microphone setup can destroy the feeling of «intimacy» and tonal «clarity». Combinative arrangements respect the fine balance that exists between high-frequency transient «clarity» (contact pickup) and low-frequency, ambient «fullness» (air transducer).

A setup that provides a «distinct», «bright» sound is illustrated in Figure 25. Concentration of energy in the 1.0KHz.-3.0KHz. area, with a maximum boost at 1.35KHz., gives an «edge» to the tone. The resultant «sharp» sound is typical of the «rock guitar» sound, which emphasizes the attack and is meant to break through dense chordal textures.

A setup emphasizing the low end is shown in Figure 26. The «solid» (u) sound is dominated by an extremely loud resonance at 280Hz., while higher resonances are less prominent.

Figure 27 reveals a configuration providing emphasis in the low and high ends. The graph illustrates a significant bass boost at 250Hz., accompanied with a high-frequency emphasis centered around 1.35KHz. The resultant

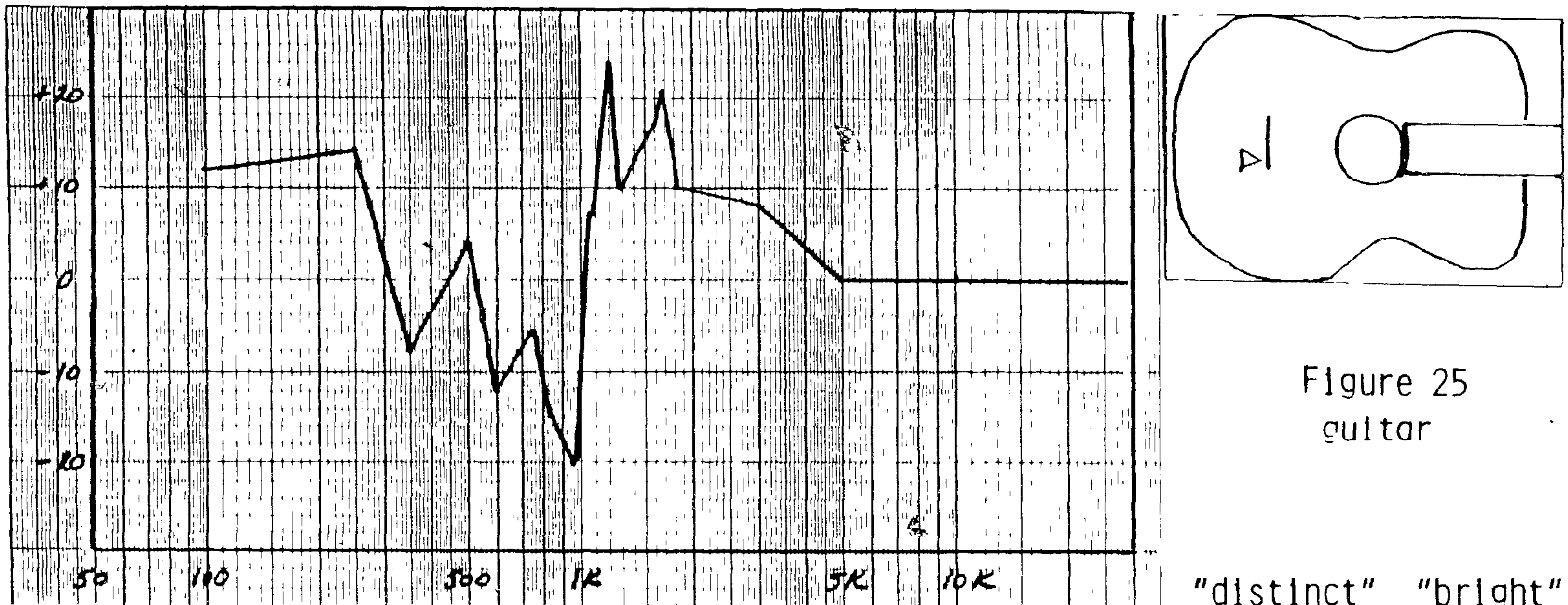


Figure 25
guitar

"distinct" "bright"

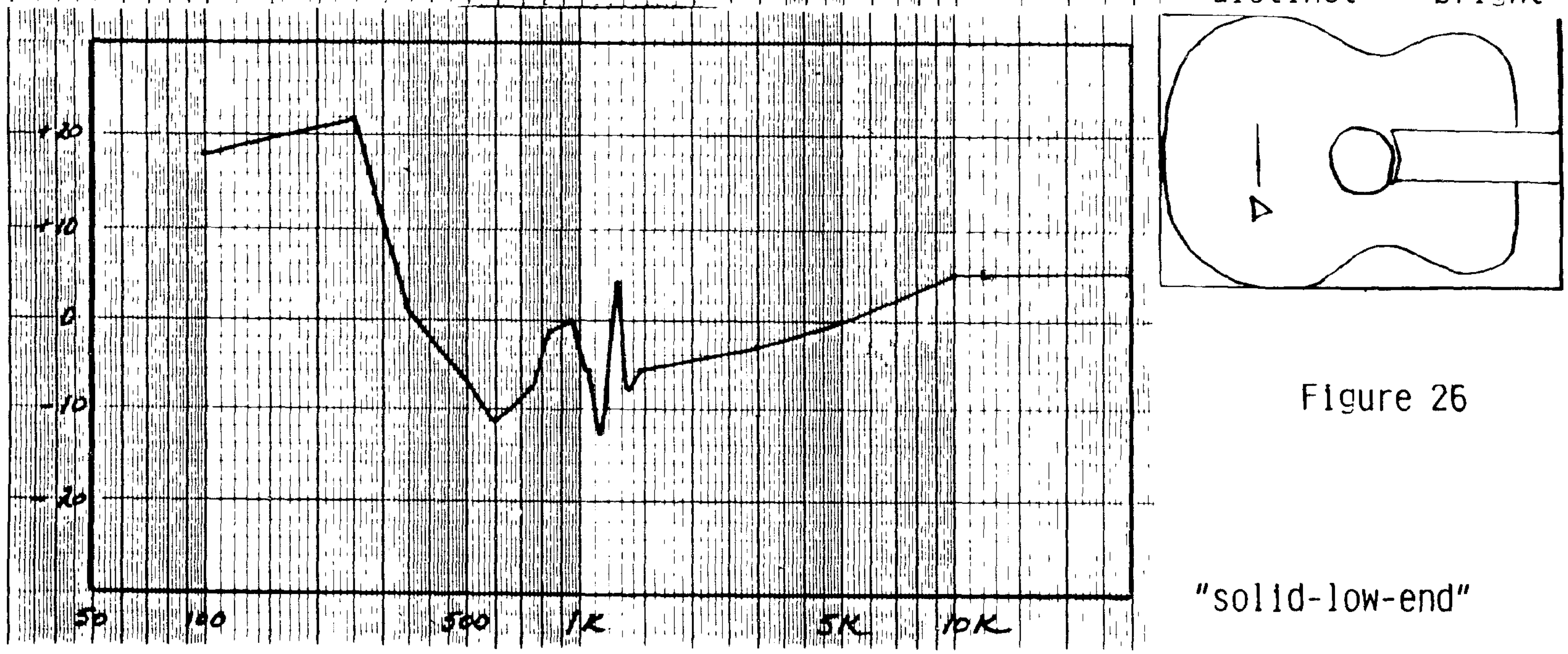


Figure 26

"solid-low-end"

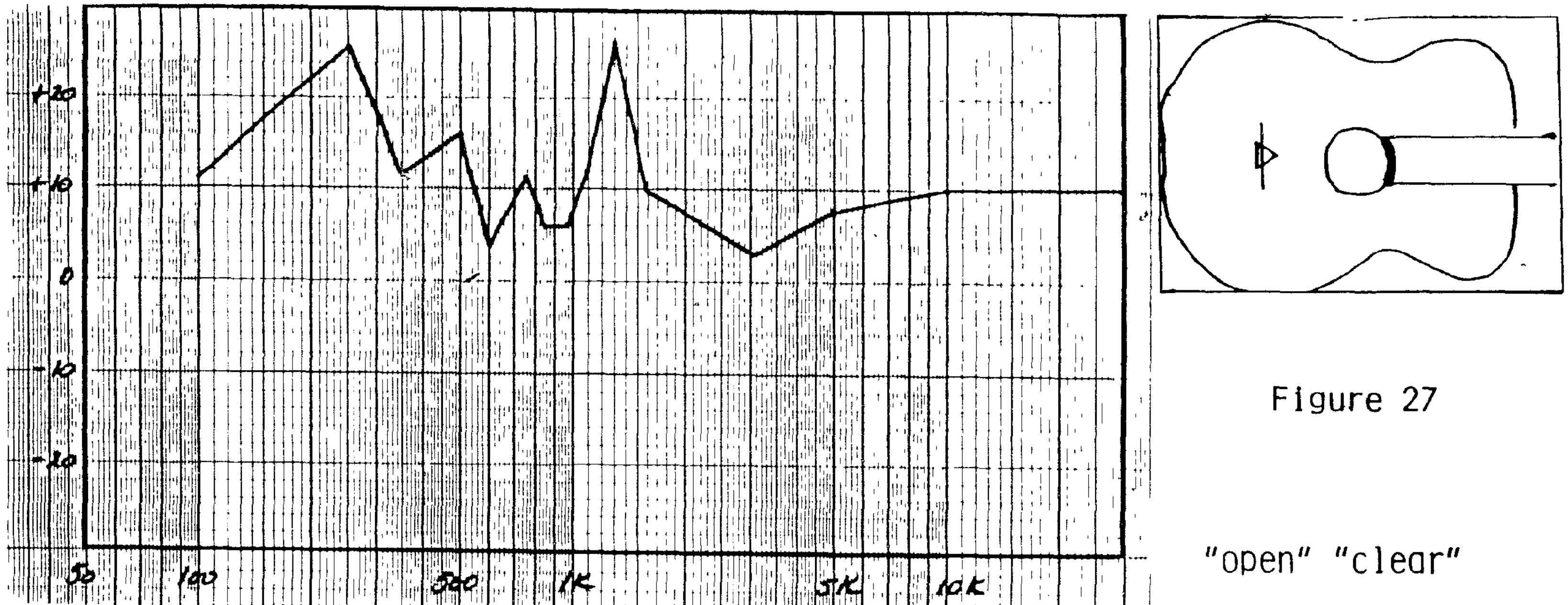


Figure 27

"open" "clear"

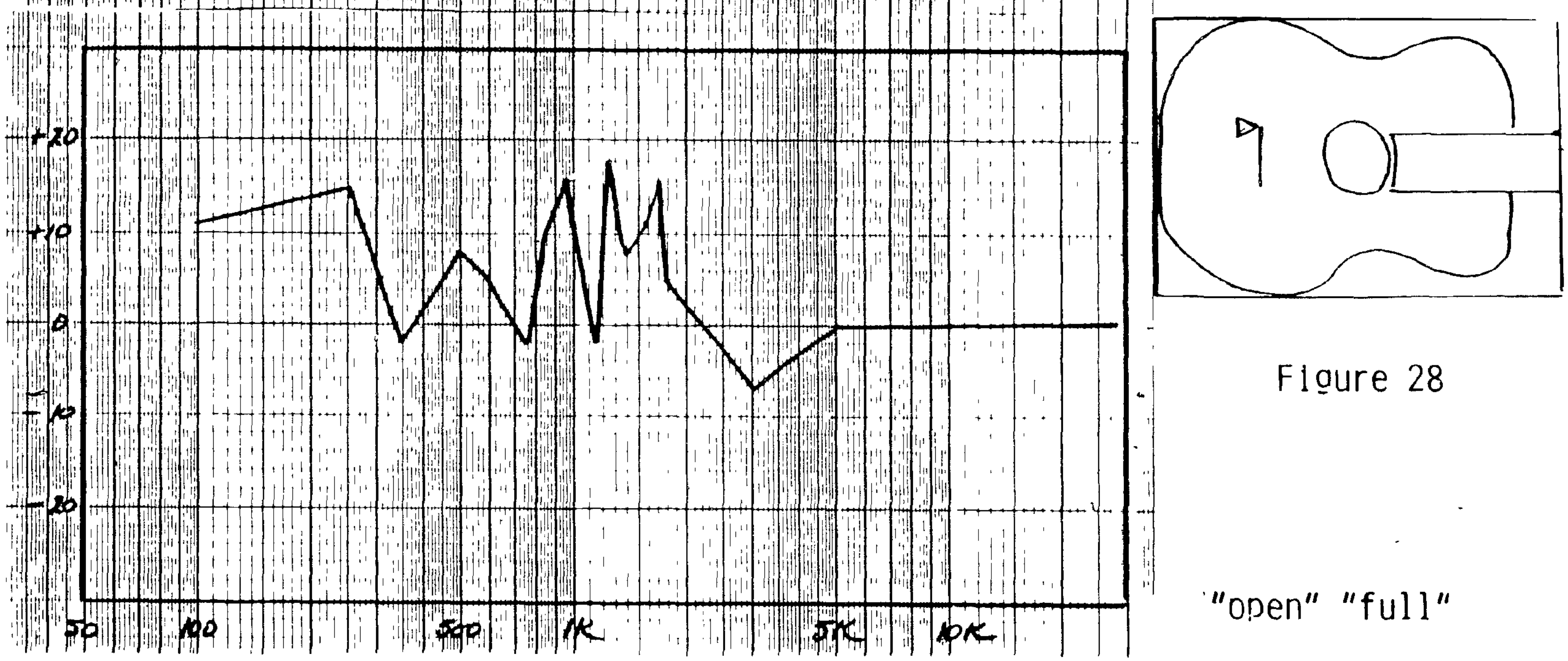


Figure 28

"open" "full"

timbre possesses an «open», «clear» (æ) quality.

More upper mid-range body is produced by the arrangement shown in Figure 28. The graph uncovers a plateau in the mid-frequencies range, 850Hz.-1.75Hz. (maximum boost at 1.35KHz.). The emphasis around 1.0KHz. contributes to an «open» (æ) sound.

SUMMARY

Combinative arrangements described in this paper take advantage of delay patterns that exist between transducer types. Even slight time shifts between two channels with similar spectra produce a recorded timbre that is not only perceived to have «depth» or «fullness» but also «spatial prominence» in the stereo image. The so-called precedence effect produced in combinative microphone arrangements is mainly responsible for these unique tonal possibilities.

The console operator can control the amount of transient emphasis without sacrificing low-frequency ambient information, by increasing the amplitude ratio between contact and air transducers. This method is thus «telescopic» in the sense that localized colours or timbres can be brought into increasingly «sharp» focus, merely by boosting the relative gain structure between channels.

The «close picture» taken by the contact further ensures against negative acoustical phase cancellations. Since each transducer type operates in independent acoustical fields, randomization of spectral information is maximized. Thus, there is greater opportunity to utilize more channels of information which in turn helps tonal characterization by natural means.

FOOTNOTES

CHAPTER 1

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B. Bartlett, «Tonal Effects of Close Microphone Placement», Journal of the Audio Engineering Society,Vol. 29 Number 10 (1981), Pp. 726-738.

2 Woszczyk, «Multimicrophone Pickup».

3 Ibid., p. 13.

CHAPTER 2

1 «Piezoelectric Accelerometers and Vibration Preamplifiers» Bruel & Kjaer Theory and Application Handbook, (1978), p. 7.

2 Ibid., p. 19.

3 A Lazarus, «The FRAP Point-Source-Microphone», dB Magazine, December (1979), p. 47.

4 «Piezoelectric Accelerometers», p. 21.

5 Ibid., p. 25.

6 Ibid., p. 27.

7 Ibid., p. 27.

8 Ibid., p. 27

9 Ibid., p. 28.

10 Ibid., p. 29.

11 Ibid., p. 29.

12 Ibid., p. 54.

CHAPTER 3

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2 Felix Savart, «The Violin», in Musical Acoustics Part 1: Violin Family Components, edited by C.M. Hutchins (Stroudsberg, Pennsylvania: Dowden, Hutchinson & Ross Inc., 1975) 15-18.

Hermann Helmholtz, On the Sensations of Tone, (New York: Dover Publications, Inc., 1954), 65-151.

3 C.M. Hutchins, «Subharmonics and Plate Top Tones in Violin Acoustics», in Musical Acoustics, Part 2: Vol. 6, ed. by C.M. Hutchins (Stroudsberg: Dowden, Hutchinson & Ross Inc., 1976) 202-209.

F.A. Saunders, «The Mechanical Action of Instruments of the Violin Family» in Musical Acoustics, Part 2: Vol. 6, ed. by C.M. Hutchins (Stroudsberg: Dowden, Hutchinson & Ross Inc., 1976) 176-193.

H.F. Meinel, «Uber die Beziethungen zwishen Holzdicke, Schwingungstorm, Körperamplitude und Klang eines Geigenkörpers» in Musical Acoustics, Pt. 2: Vol. 6, ed. C.M. Hutchins (Stroudsberg: Dowden, Hutchinson & Ross Inc., 1976) p. 72.

E.V. Jansson, et al., «Resonances of a Violin Body Studied by Hologram Inter-ferometry and Acoustical Methods» in Musical Acoustics, Pt. 2: Vol. 6, ed. C.M. Hutchins (Stroudsberg: Dowden, Hutchinson & Ross Inc., 1976) 131-144.

4 C.M. Hutchins, «The Physics of Violins», in The Physics of Music, edited by C.M. Hutchins (San Francisco: W.H. Freeman and Company, 1978) p. 61.

5 Ibid., p. 63

6 Ibid., p. 62.

7 Ibid., p. 61.

8 Saunders, «The Mechanical Action of Instruments», 176-193.

9 Ibid., p. 186.

10 Hutchins, «The Physics of Violins», p. 64.

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1 H. Helmholtz, On the Sensations of Tone, (New York: Dover Publications, ~~Inc~~., 1954), 80-118.

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3 Ibid., p. 16.

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5 E. Jansson, «Analogies between bowed string instruments and the human voice, source-filter methods», STL-QPSR 3/1966 4-6.

6 Sundberg, «The Acoustics of the Singing Voice», p. 17.

7 Ibid., p. 18.

8 Ibid., p. 19.

9 Ladefoged, A Course in Phonetics, p. 168.

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11 A.W. Slawson, «Vowel Quality and Musical Timbre as Functions of Spectrum Envelope and Fundamental Frequency», J.A.S.A., Vol. 43 No. 1. 1968. 87-101.

12 Ibid., p. 88

13 Ibid., p. 97.

14 F. Winckel, Music Sound and Sensation, (New York: Dover Publications, Inc., 1967) p. 42.

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16 Slawson, «The Color of Sound: A Theoretical Study in Musical Timbre», Music Theory Spectrum, (1982) 132-141.

17 For example, timbres described as «open» exhibit a high-

first formant. In terms of the vowels chosen for this study (æ) would be classified as the most «open», while (i) would be «non-open» (see Figure 1). An «acute» timbre corresponds with a high second formant (i), while (u) is «non-acute». A «lax» timbre corresponds with a «neutral» or «unstressed» vowel.

Although the basic plan of Slawson's study is derived from acoustic phonetic theory, the distinctive timbral features may be easily heard. These vocal analogies appear to fit quite naturally. The fact that vowel perception is in-built, requiring no external device for analysis, makes this system of timbral composition simple, yet effective.

18 John Grey, «An Exploration of Musical Timbre», Ph.D. Thesis Stanford University Dep't of Music Report No. Stan-M2. 1975.

19 Ibid., p. 4.

20 J.H. Moral, E. Jansson, «Long-time-average-spectra of scales and spectra of single tones from a violin», STL-QPSR 1/1978, 30-39.

For example, the ear's ability to integrate acoustical stimulation has been empirically established. The ear can be represented by a series of 24 third-octave band-pass filters. The amplitude output of the various filters are weighted differently so that variations of sensitivity of the ear is taken into consideration. In general, low weighting is applied to the low and high ends of the spectrum, while a higher weighting is given to the middle frequencies. Only in the lowest portion of the spectrum (i.e., covering the first six harmonics) is the ear particularly sensitive to individual peaks. Thus, a formant model theory (used in this case, for the description of musical timbre) is compatible with the filtering action of the ear.

21 Grey, «An Exploration», p. 5.

22 Ladefoged, A Course in Phonetics, p. 170.

23 Helmholtz, On the Sensations of Tone, p. 103.

24 Yankovskii, «Methods for the Objective Appraisal», p. 305.

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26 Ibid., p. 311.

27 F. Toole, «Listening Tests-Turning Opinion into Fact», Journal of the Audio Engineering Society, Vol. 30 No 6 1982. p. 438.

28 B. Bartlett, «Tonal Effects of Close Microphone Placement», J.A.E.S. Vol. 29 No. 10 1981. 726-738.

29 Meyer, «Acoustics and the Performance of Music», p. 61.

CHAPTER 5

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2 A. Lazarus, «The FRAP Point-Source Microphone», dB Magazine (Plainview, N.Y.: Sagamore Publishing Co., Inc., 1979.) 47-51.

3 Woszczyk, «Multimicrophone», p. 17.

4 Ibid., p. 18.

5 Meyer discovered a persistent peak at 1.6KHz., which was responsible for this quality in the viola.

6 Lazarus «The FRAP», p. 48.

7 Refer to Appendix III.

8 A. Lazarus, «The Use of the FRAP (Flat Response Audio Pickup) in Professional Recording», A.E.S. pre-print 952 (D-4) 1974. p. 5.

9 Meyer, Acoustics, p. 55.

10 Lazarus, «The Use of the FRAP», p. 5.

11 Meyer, Acoustics, p. 69.

12 Lazarus, «The Use of the FRAP», p. 5.

13 Meyer, Acoustics, p.

14 The bass bar is a separate piece of wood which supports the pegs to which the bass strings are attached.

15 Lazarus, «The Use of the FRAP», p. 5.

16. Ibid., p. 5.

C H A P T E R 6

1 W. Woszczyk, «Multimicrophone», p. 13.

B. Bartlett, «Tonal Effects», p. 737.

2 Woszczyk, «Multimicrophone», p. 6.

3 G. Boré, Microphones for professional and semi professional applications translated by Stephen F. Temmer, p. 57.

4 Taken after Bartlett's study of the tonal effects of close microphone arrangements, these graphs show the effect of the contact pickup. Conclusions can then be made on the cumulative effect of each arrangement, on the timbre.

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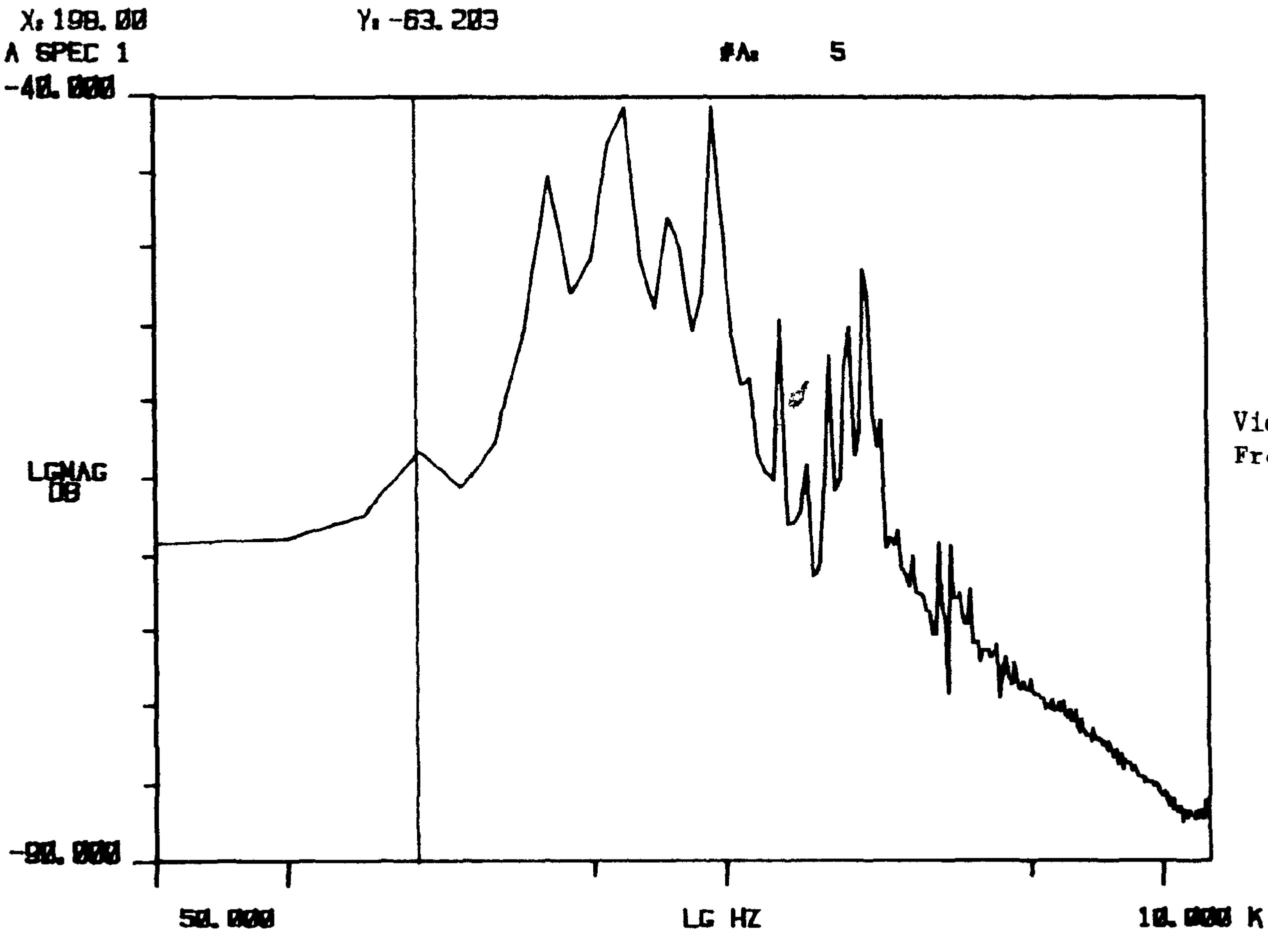
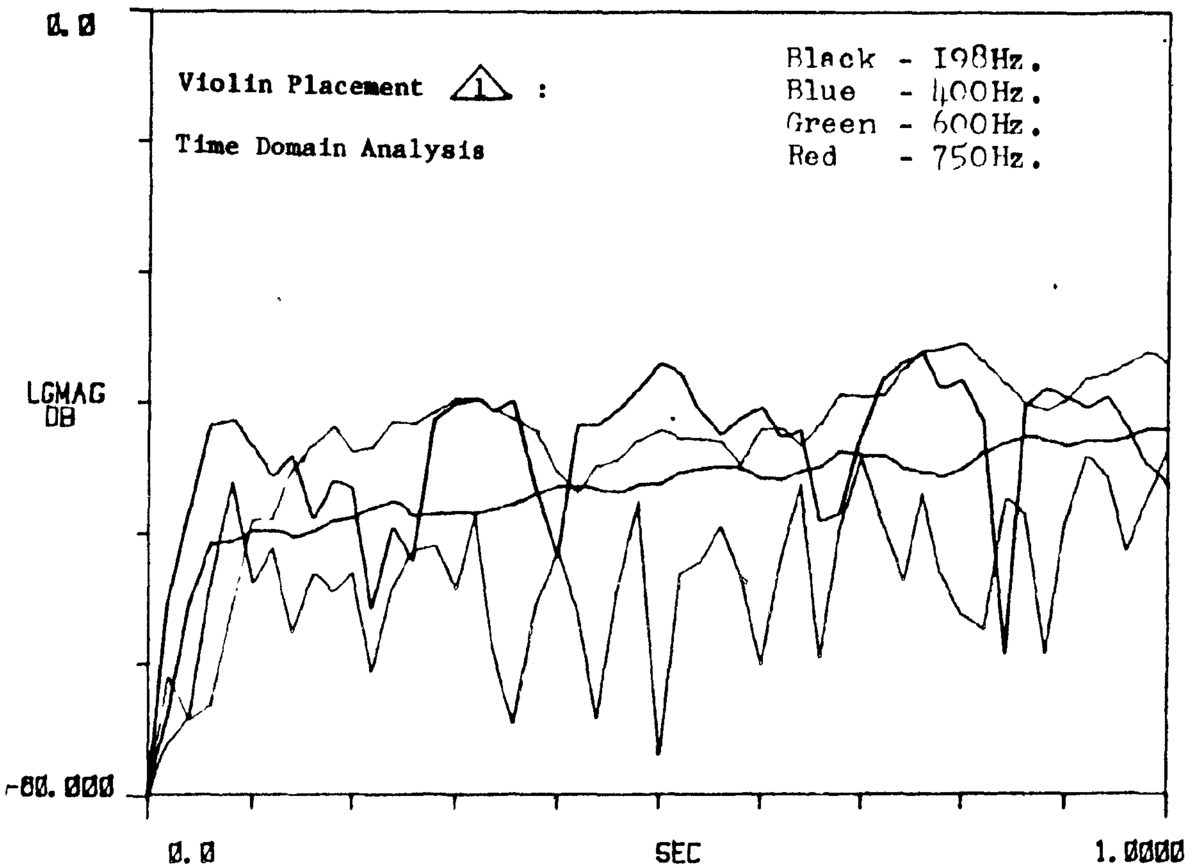
APPENDIX I

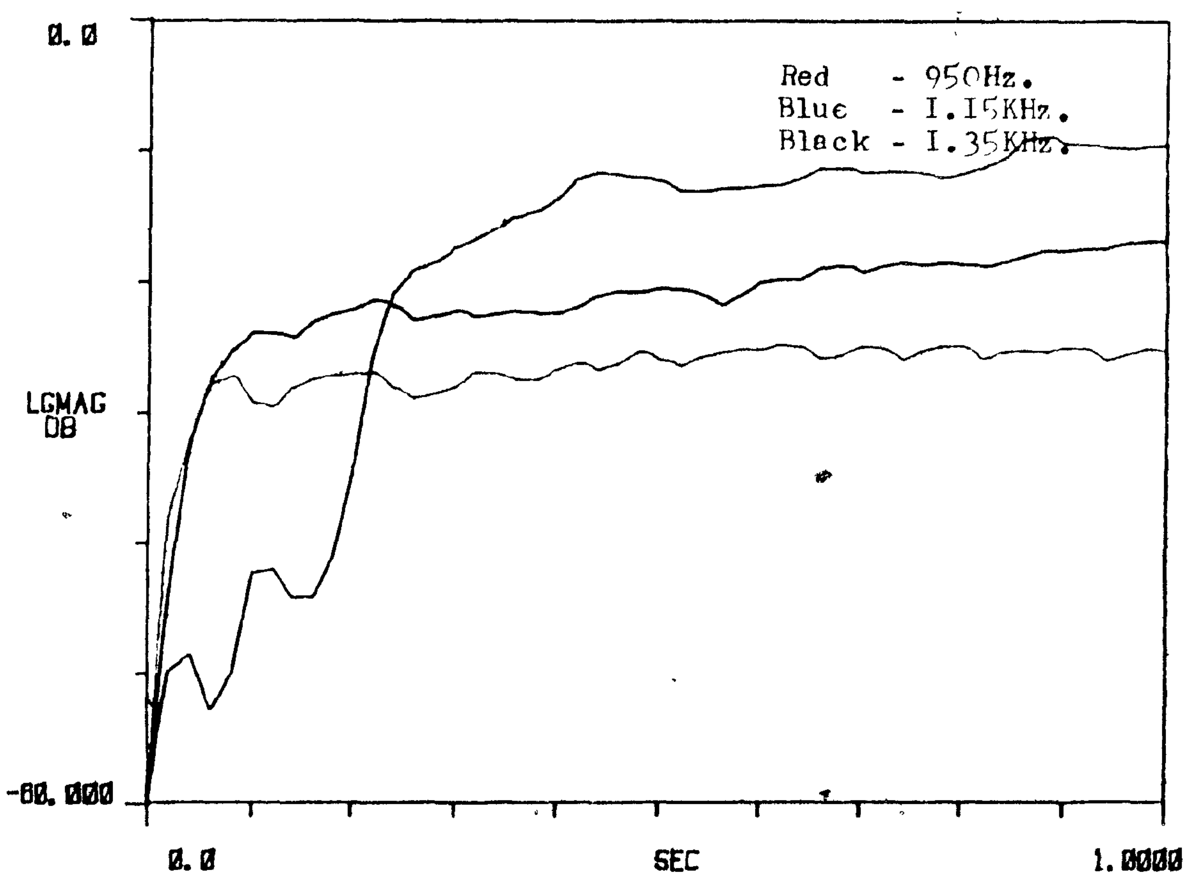
Violin

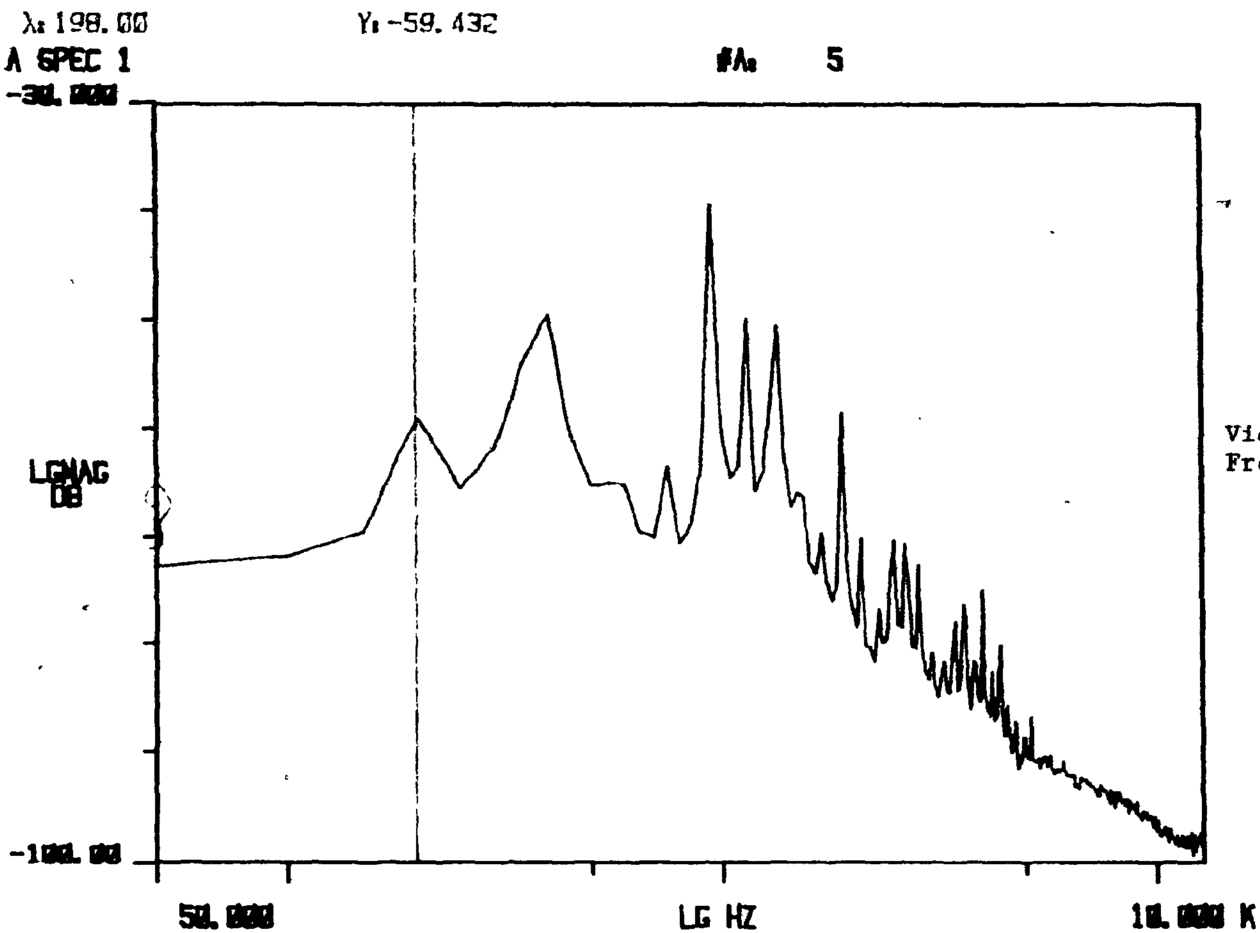
Spectrum Analysis



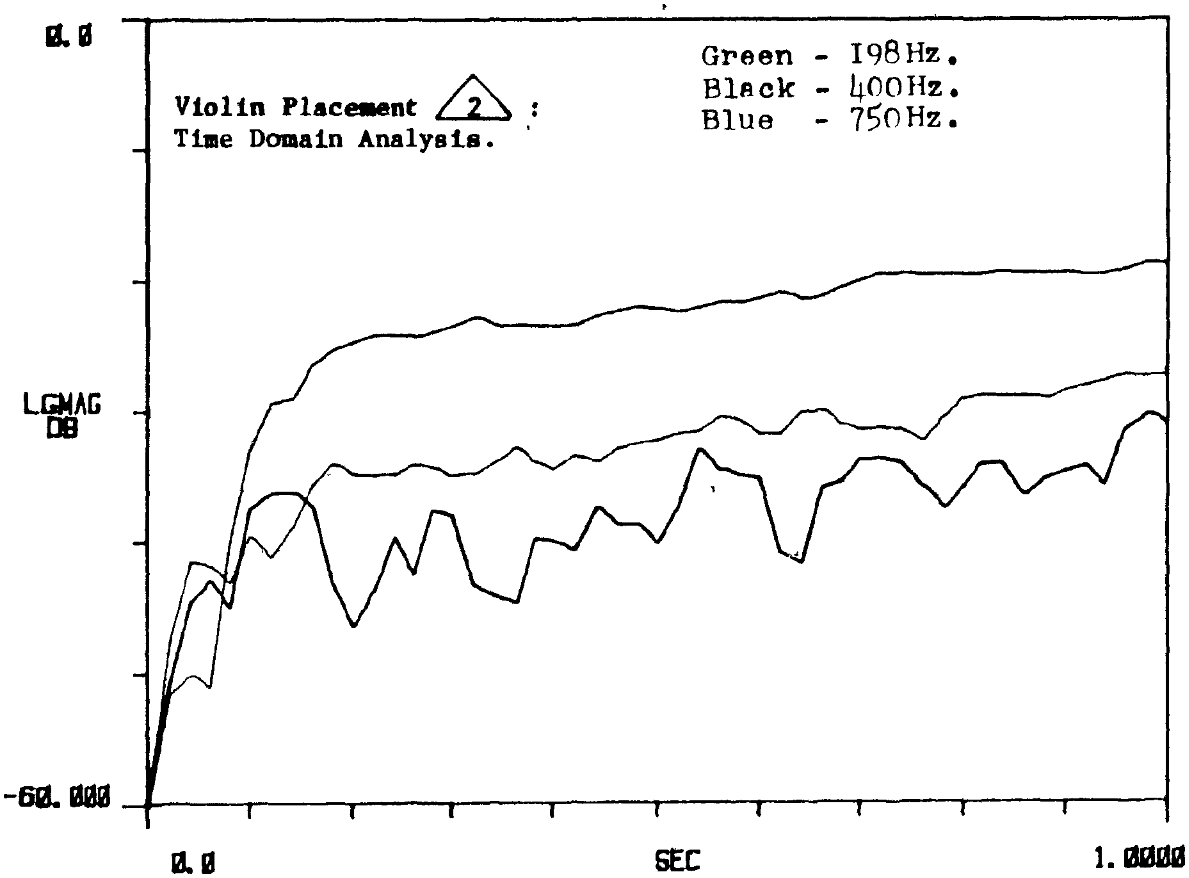
Violin Placement (1) :
Frequency Domain Analysis

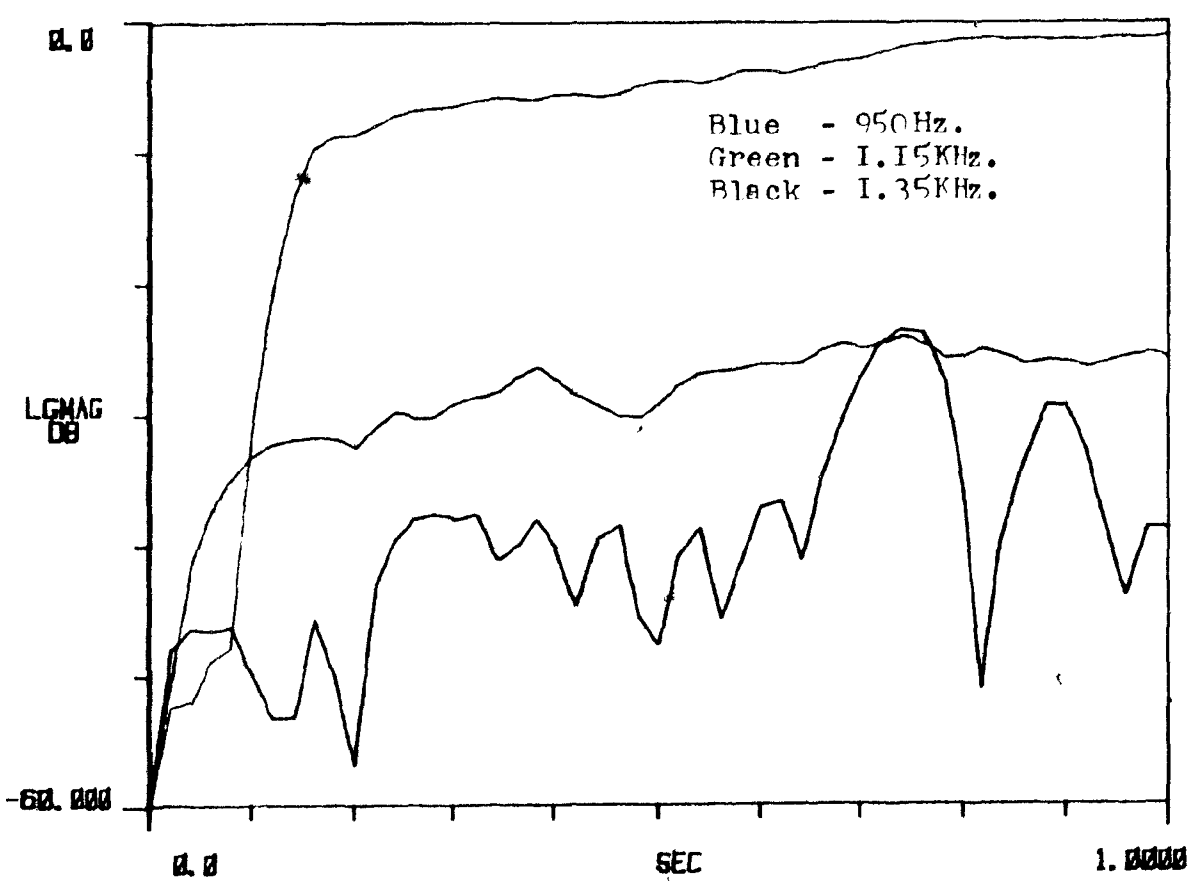

0.0
Violin Placement 1 :
Time Domain Analysis
Black - 198Hz.
Blue - 400Hz.
Green - 600Hz.
Red - 750Hz.
LGMAG DB
-60.000
0.0
SEC
1.0000

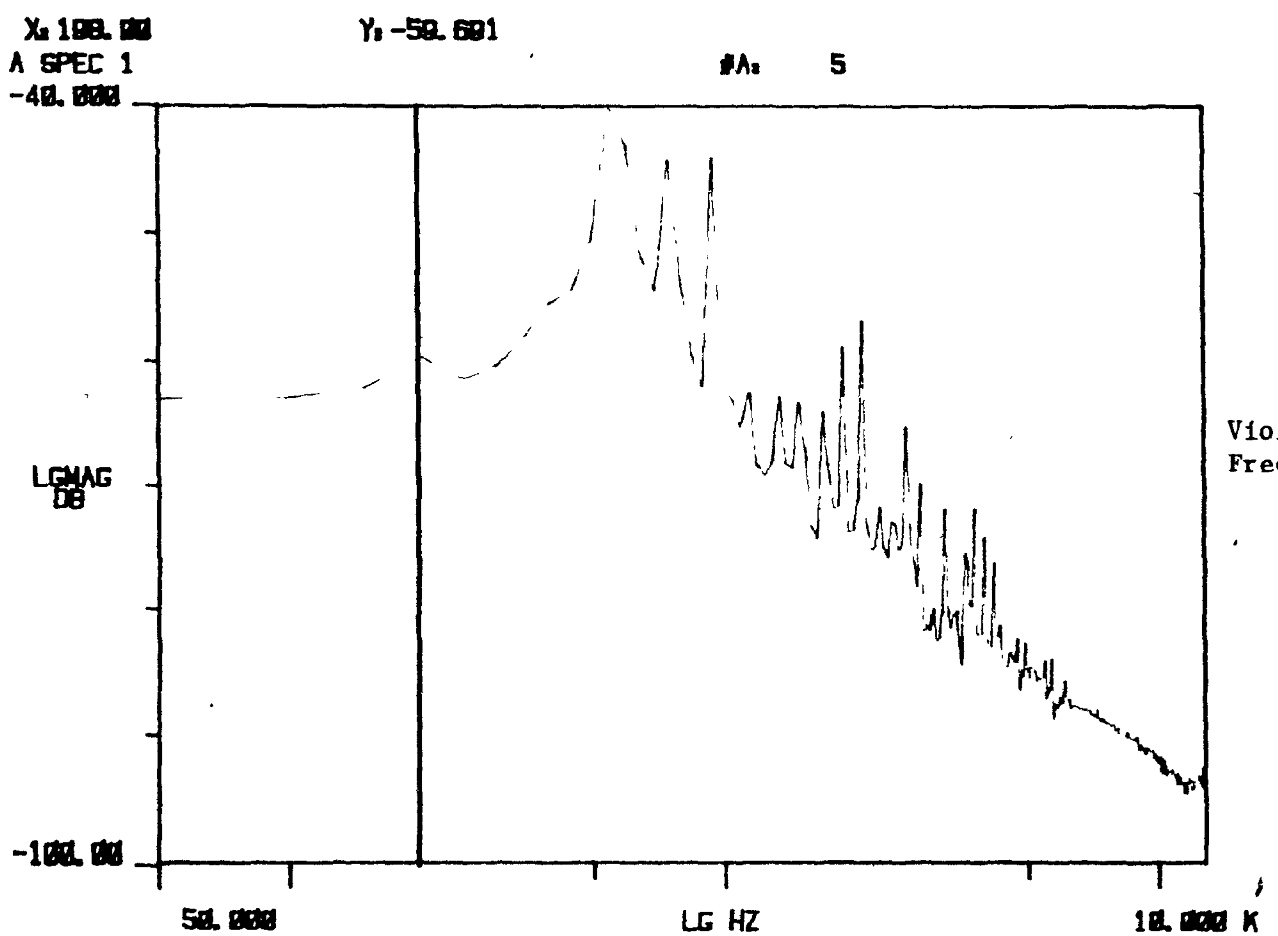

0.0
Red - 950Hz.
Blue - 1.15KHz.
Black - 1.35KHz.
LGMAG DB
-60.000
0.0
SEC
1.0000



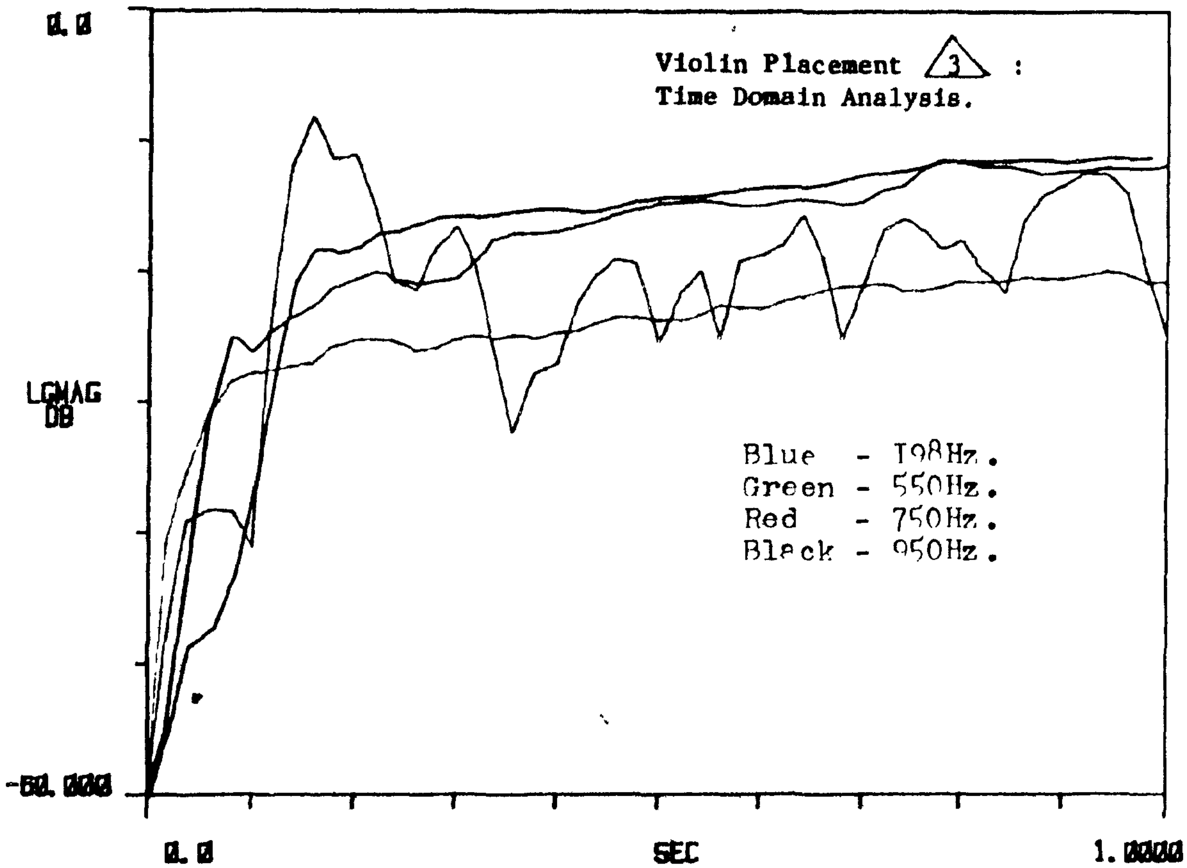
Violin Placement (2) :
Frequency Domain Analysis.


Violin Placement 2 :
Time Domain Analysis.
Green - 198Hz.
Black - 400Hz.
Blue - 750Hz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000

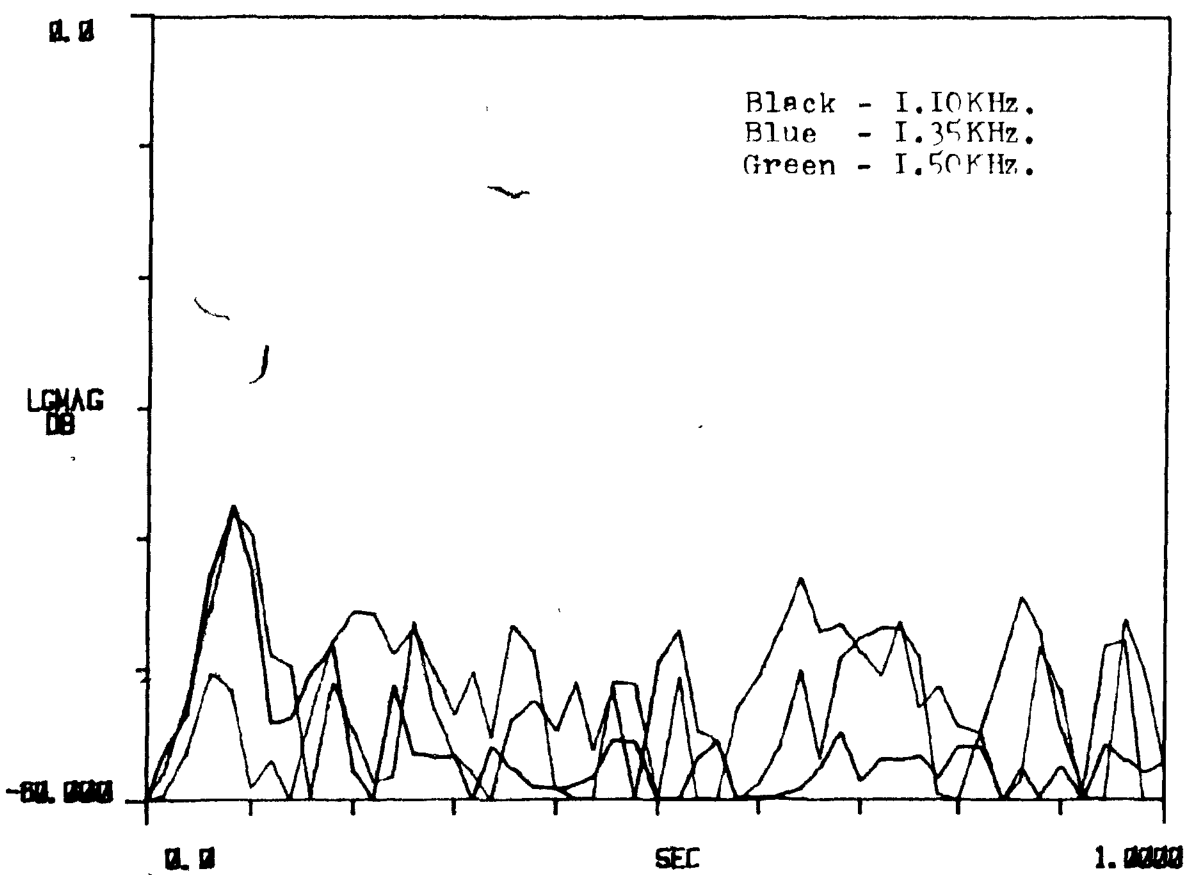

Blue - 950Hz.
Green - 1.15KHz.
Black - 1.35KHz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000



Violin Placement (3):
Frequency Domain Analysis.

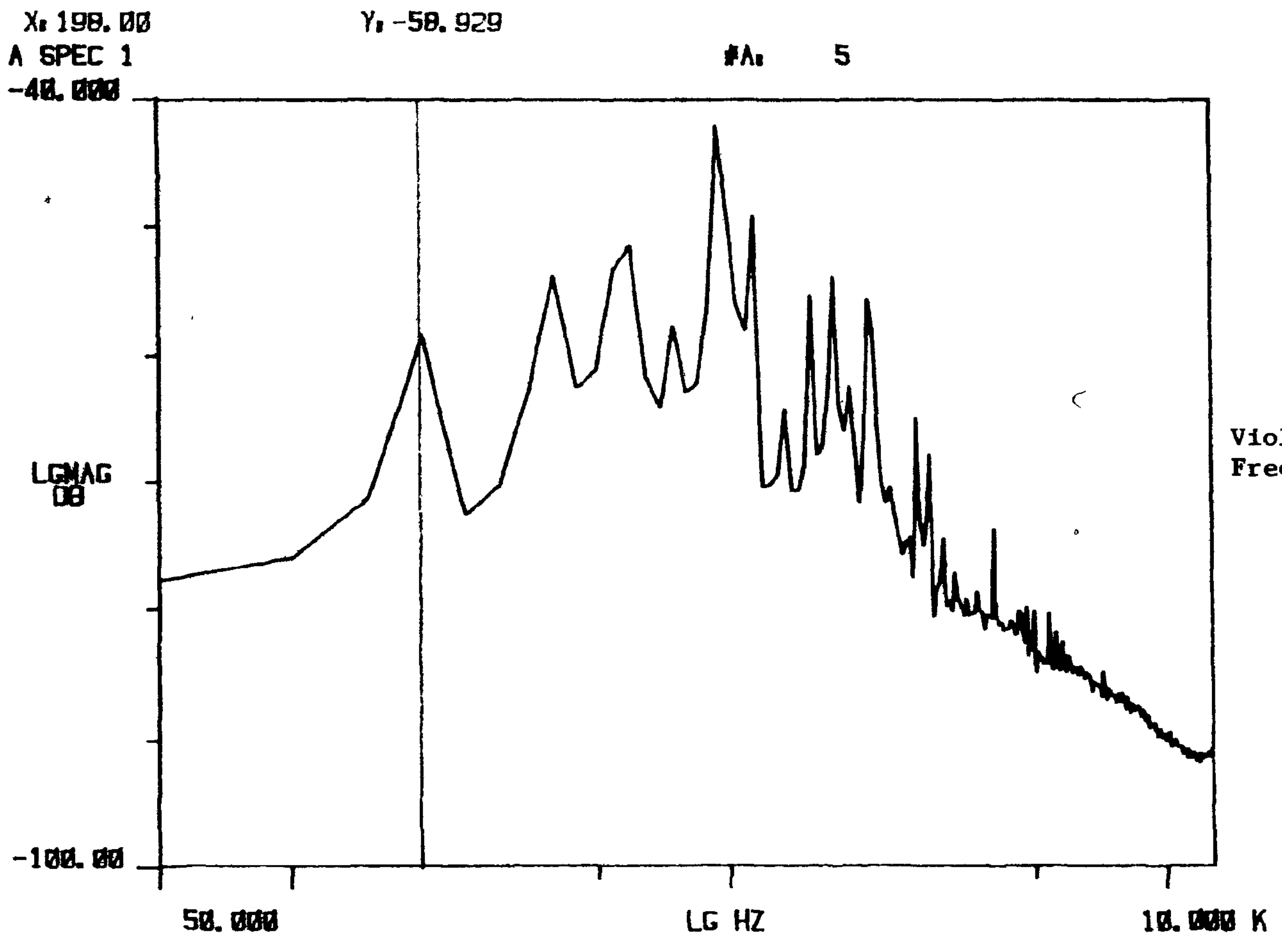


0.0
Violin Placement 3 :
Time Domain Analysis.
LGMAG
DB
Blue - 198Hz.
Green - 550Hz.
Red - 750Hz.
Black - 950Hz.
-60.000
0.0
SEC
1.0000

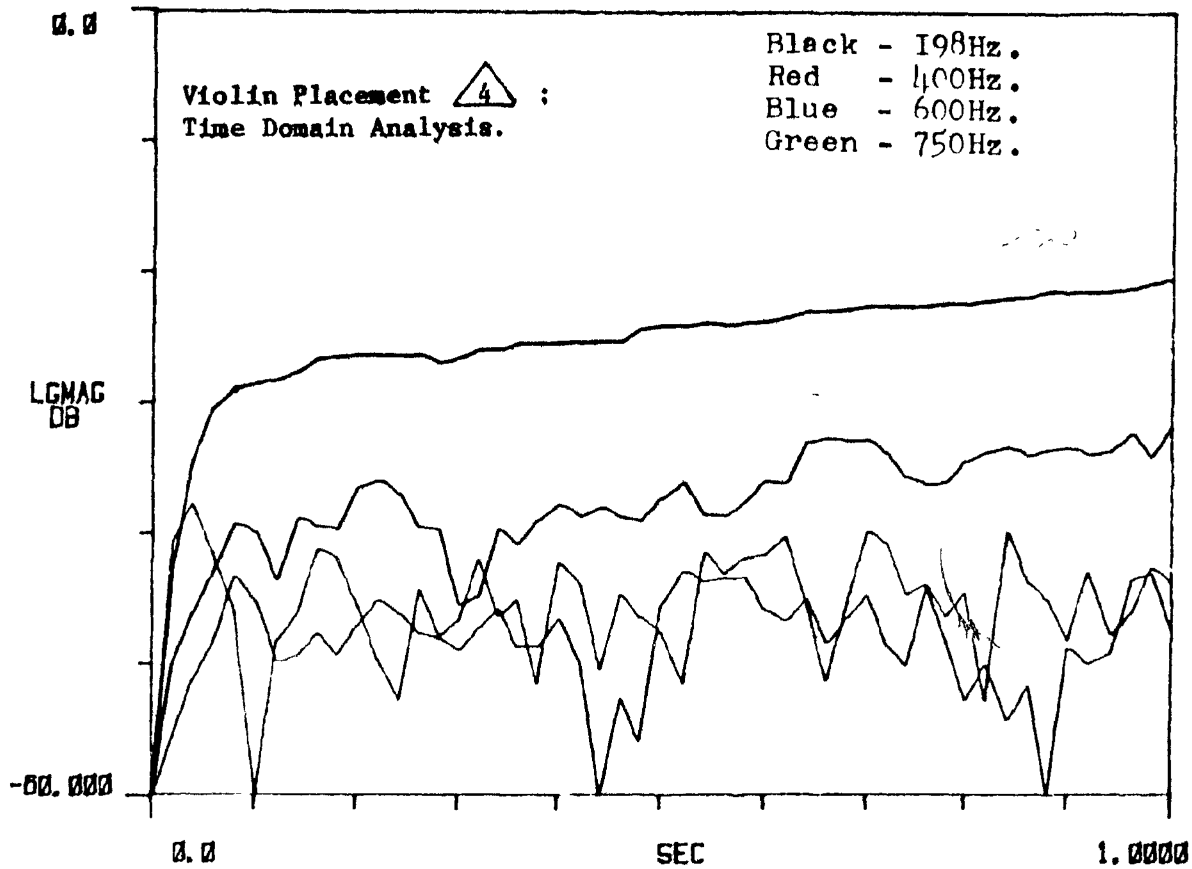


0.0
Black - 1.10KHz.
Blue - 1.35KHz.
Green - 1.50KHz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

125



Violin Placement 4 ;
Frequency Domain Analysis.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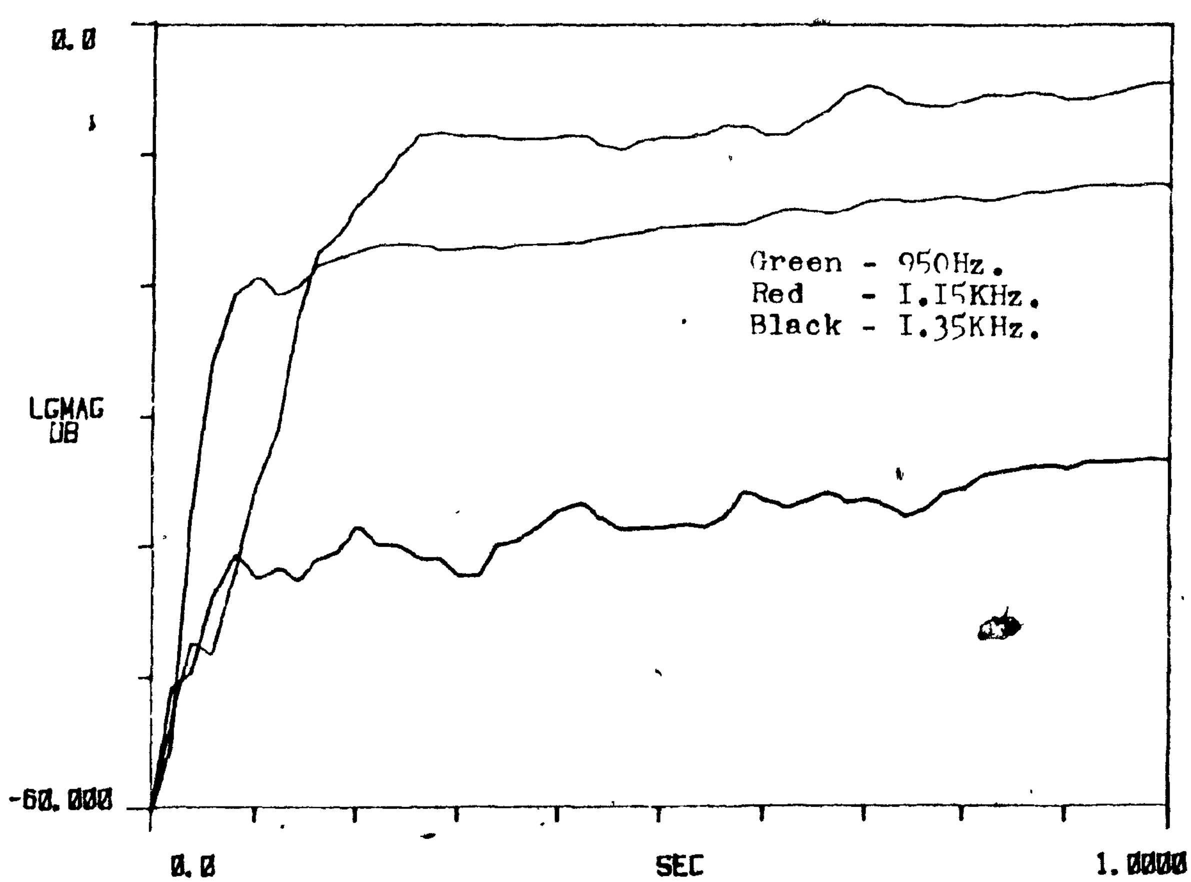
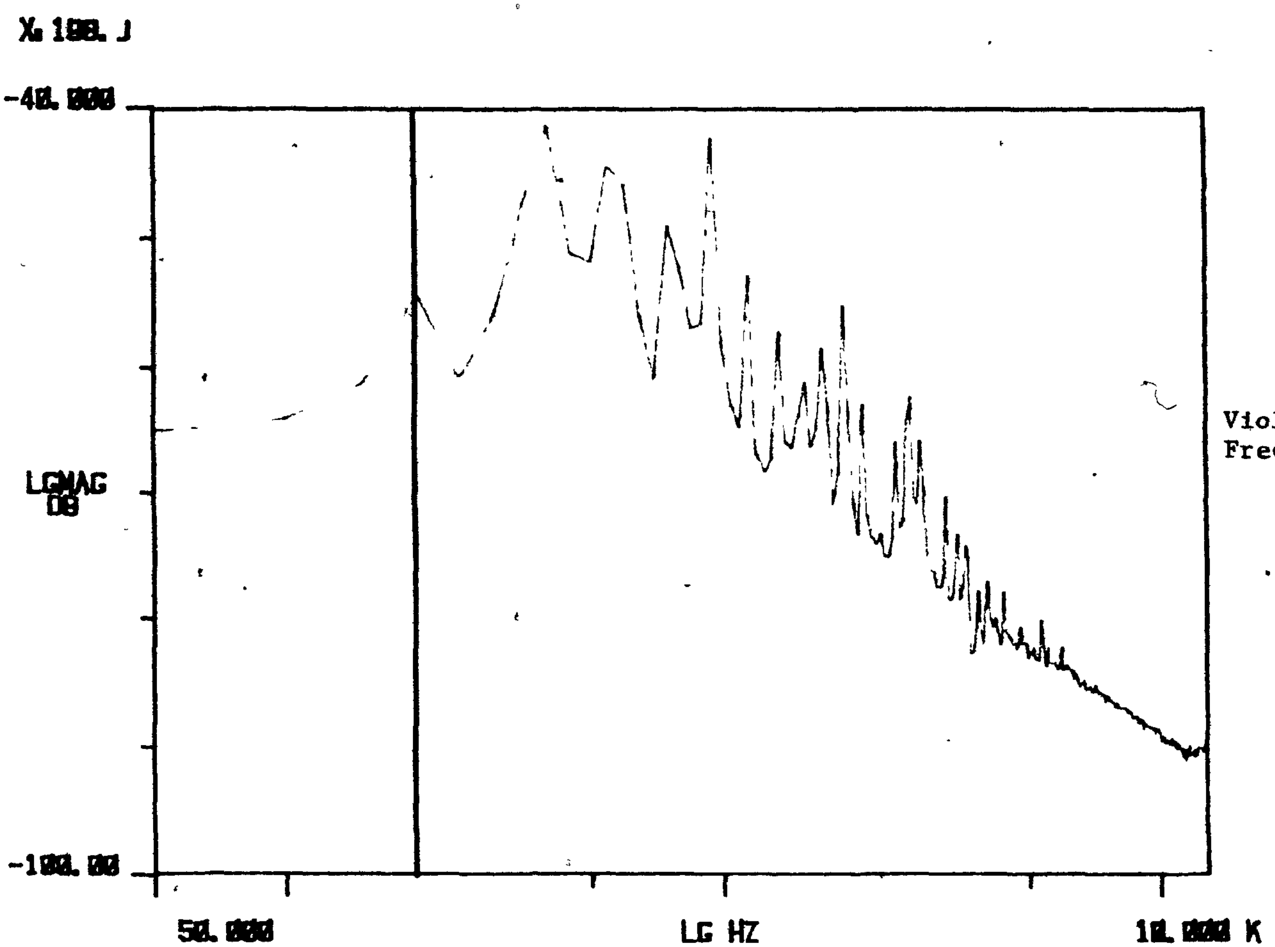
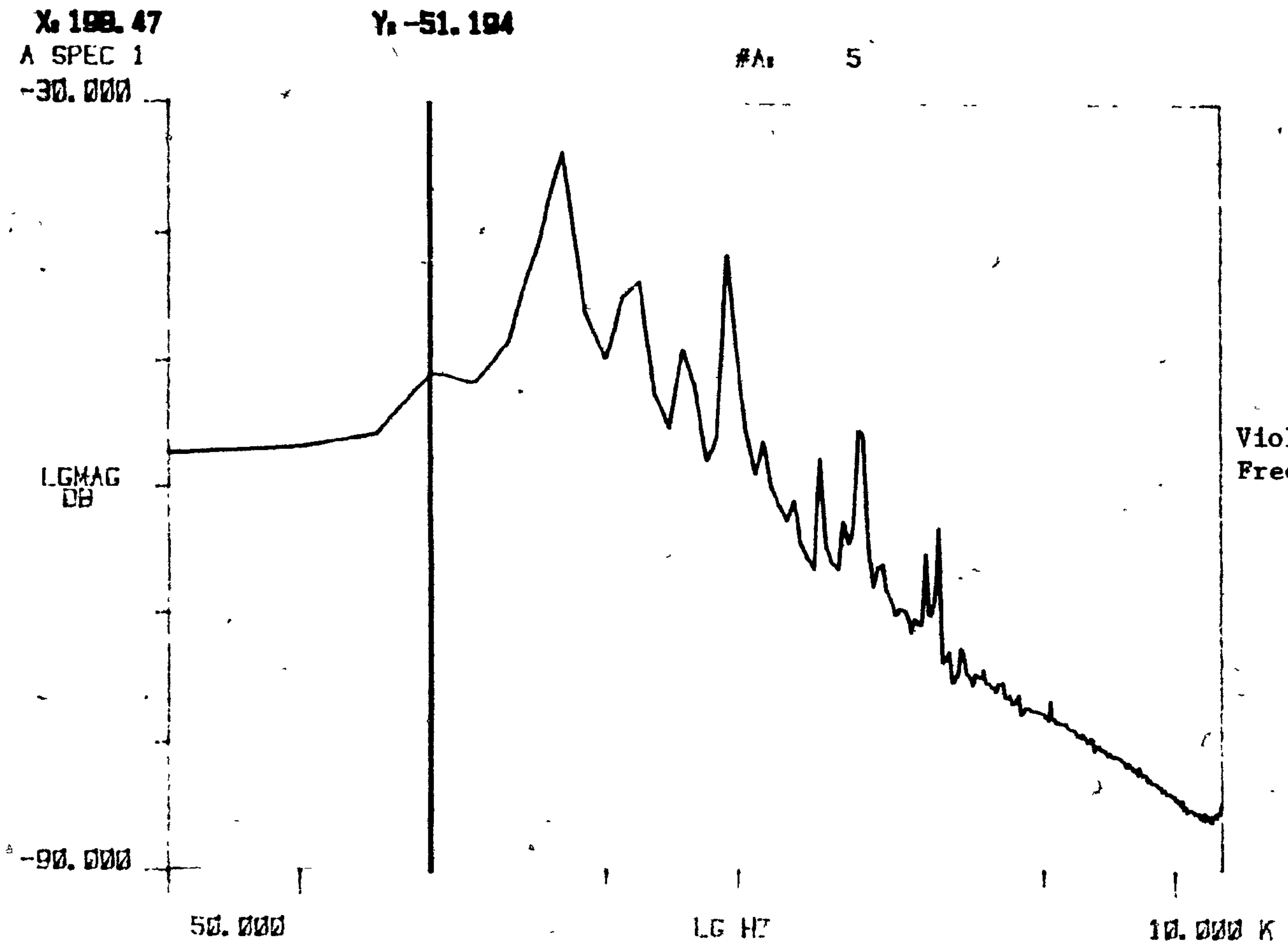
Violin Placement 4 :
Time Domain Analysis.
Black - 198Hz.
Red - 400Hz.
Blue - 600Hz.
Green - 750Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

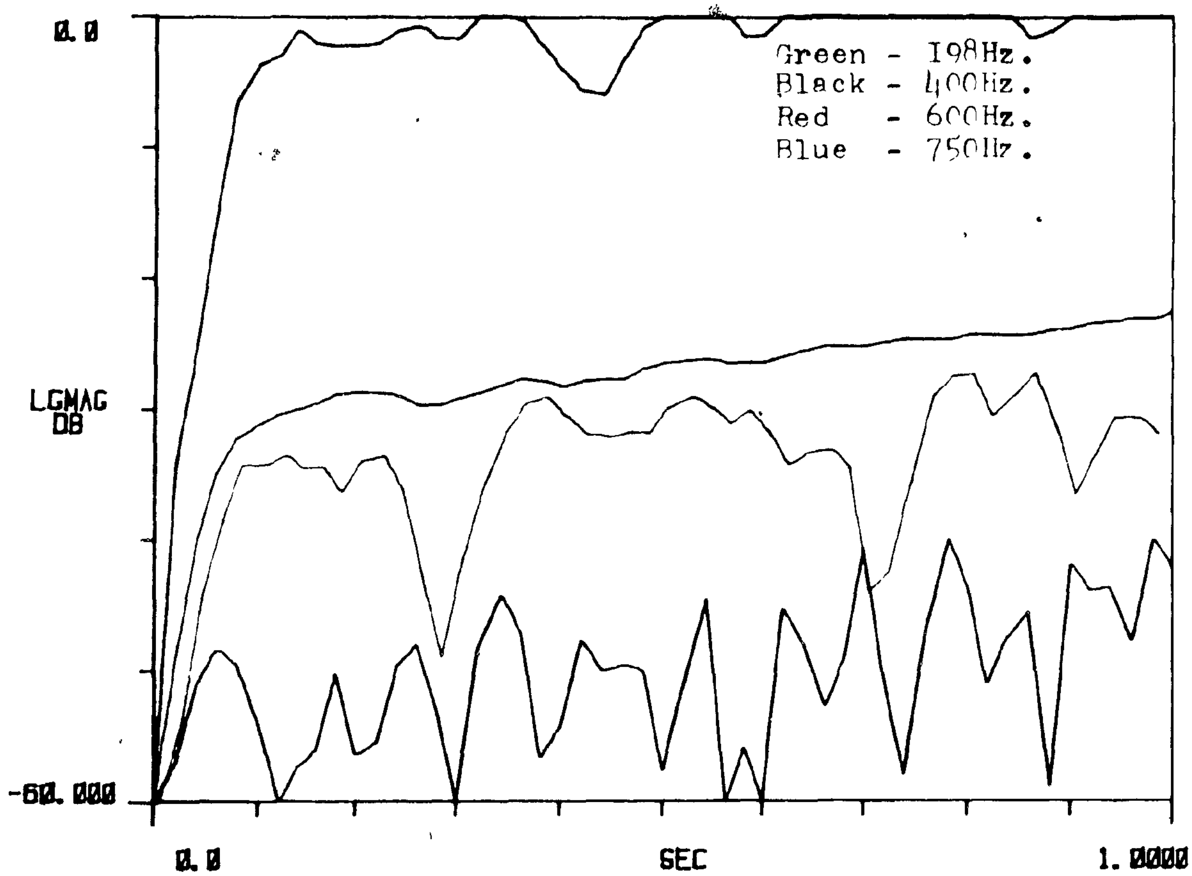

0.0
Green - 950Hz.
Red - I.I5KHz.
Black - I.35KHz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

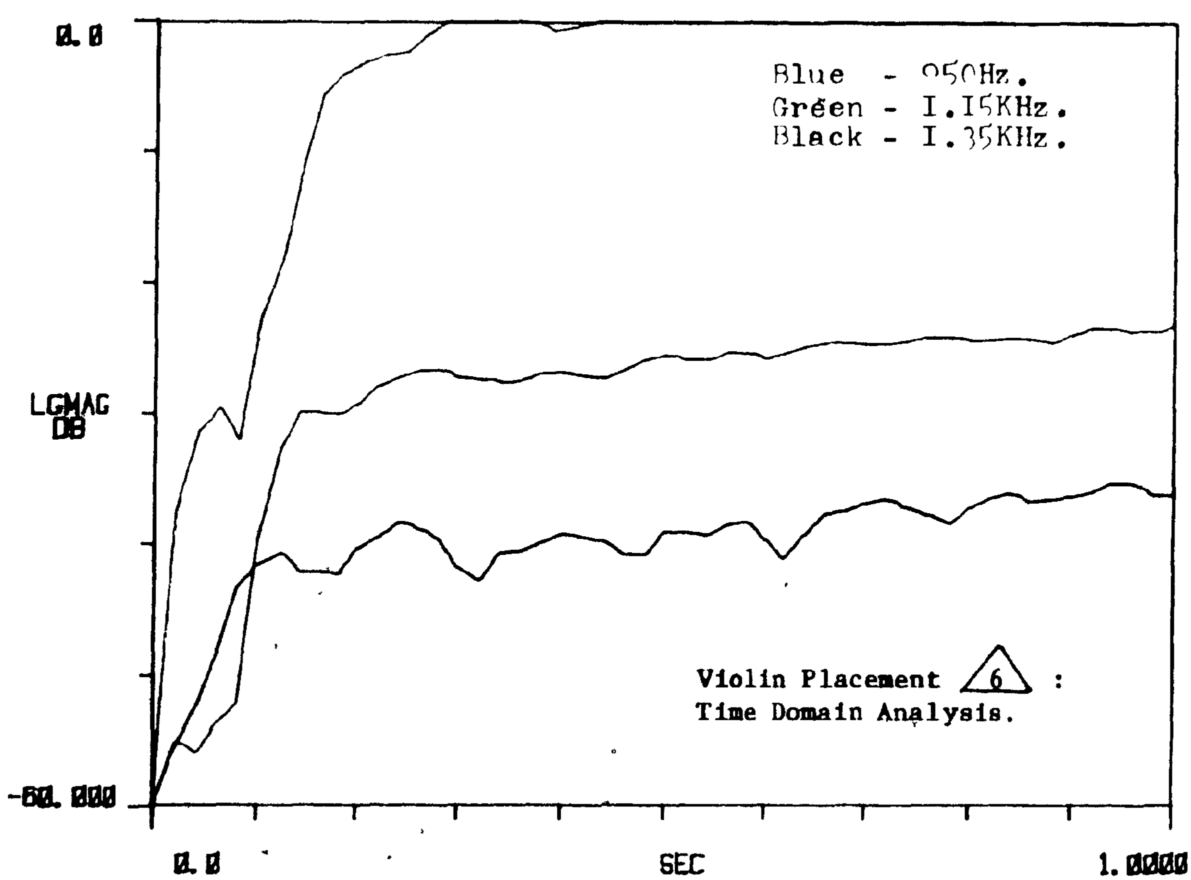


Violin Placement 5 :
Frequency Domain Analsis.

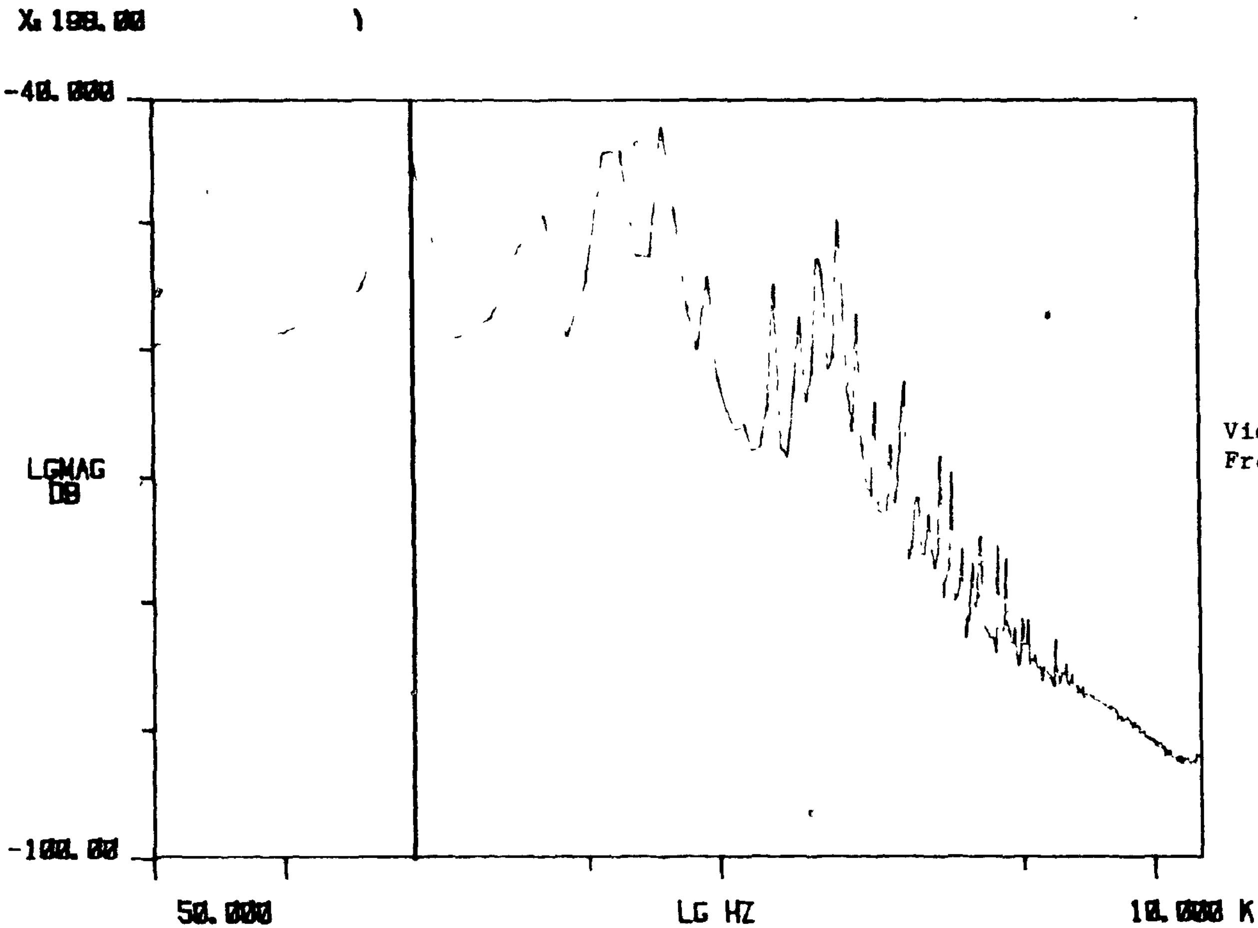


Violin Placement 6 :
Frequency Domain Analysis.

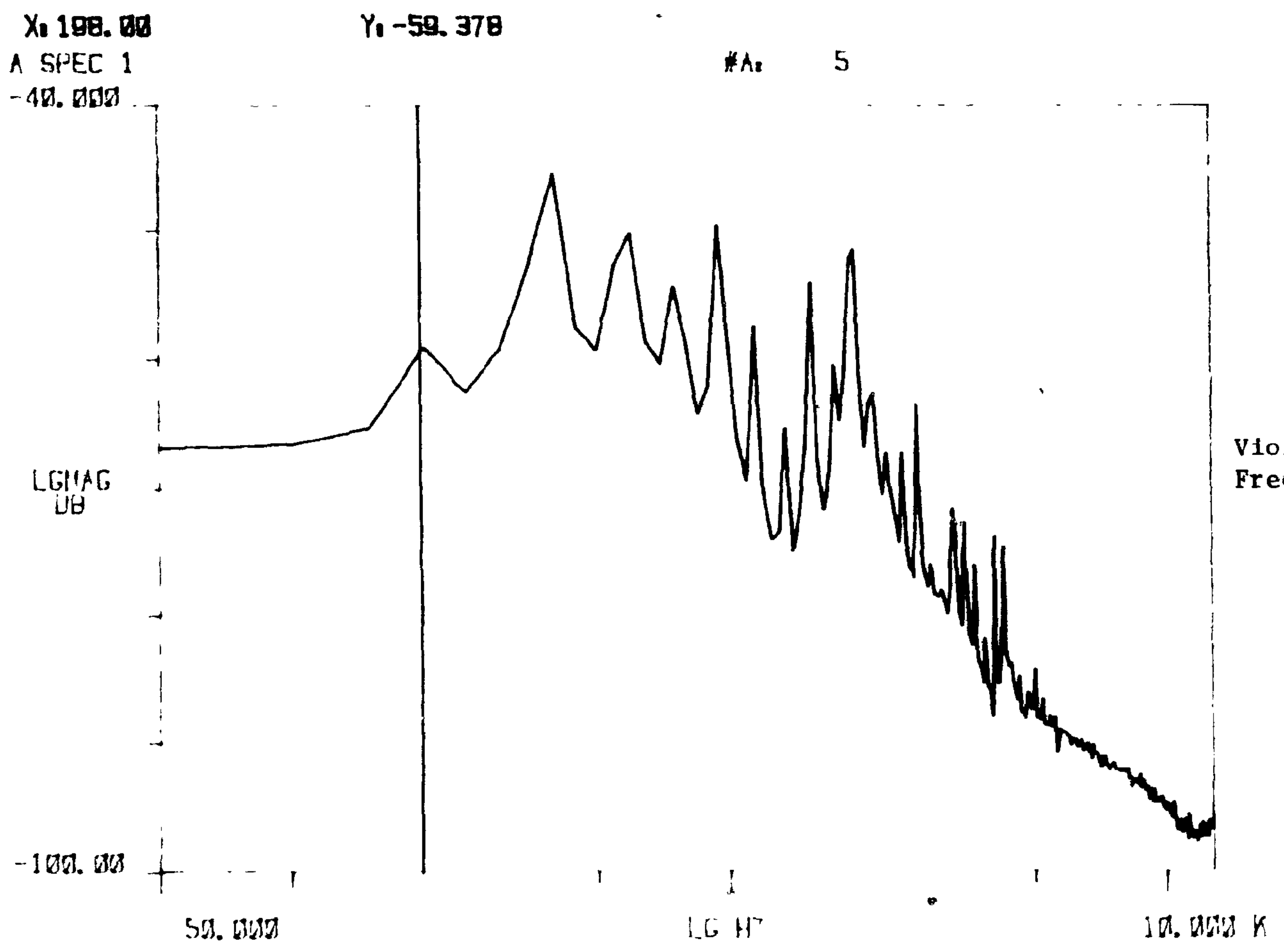




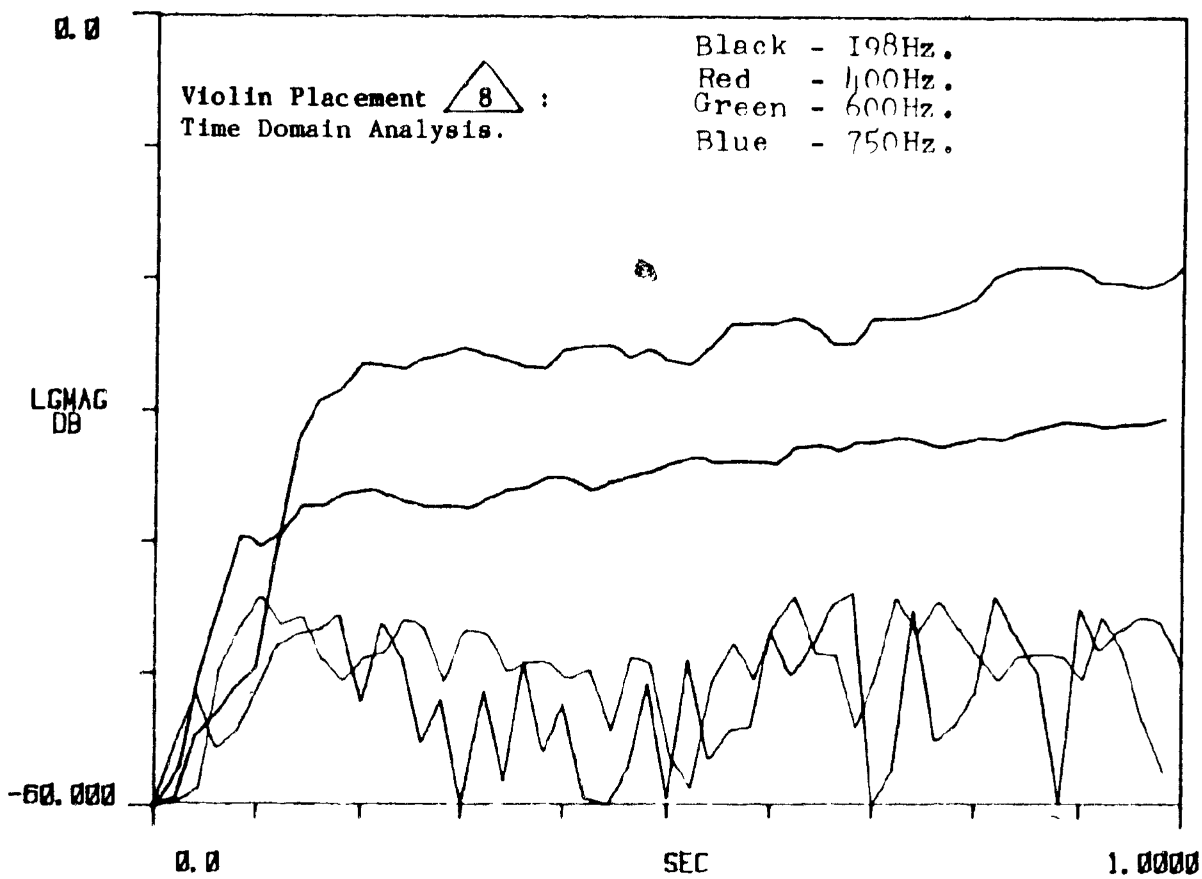
Violin Placement 6 **:**
Time Domain Analysis.

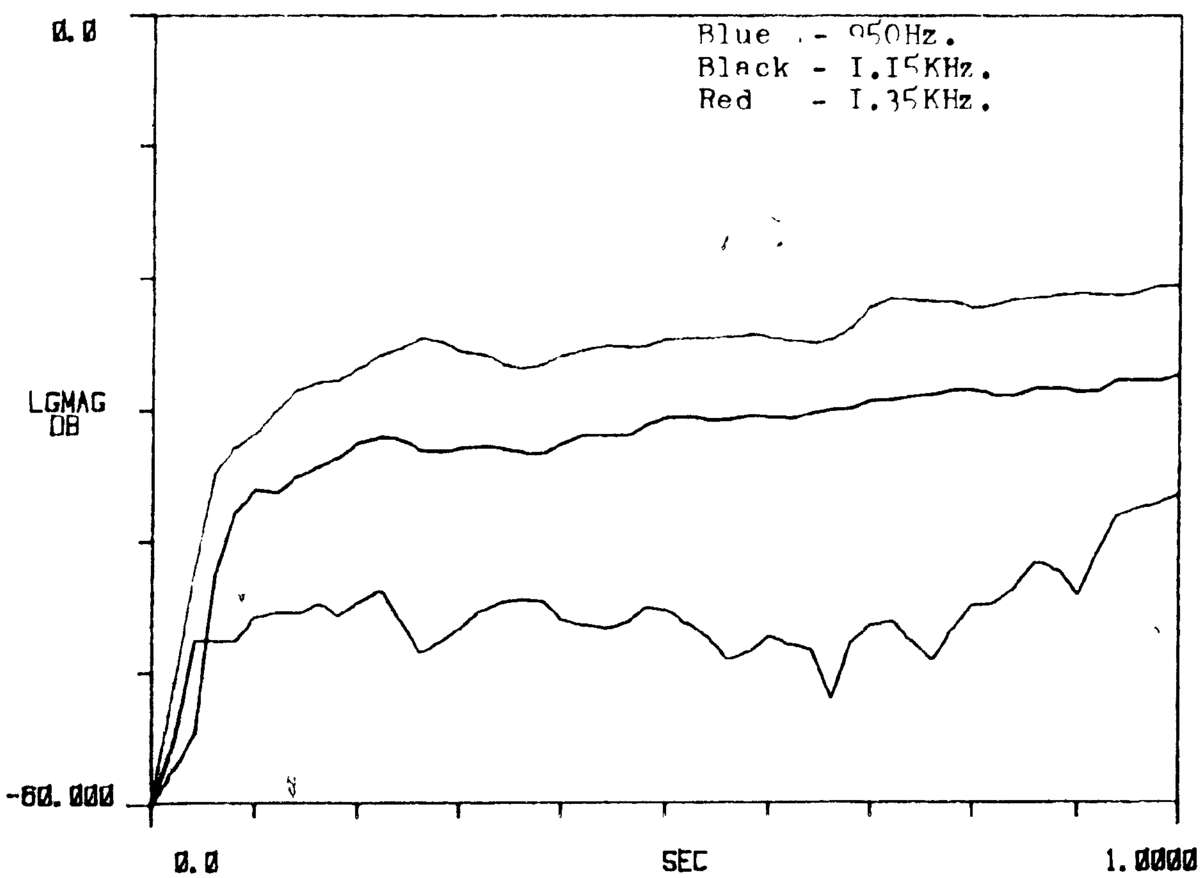


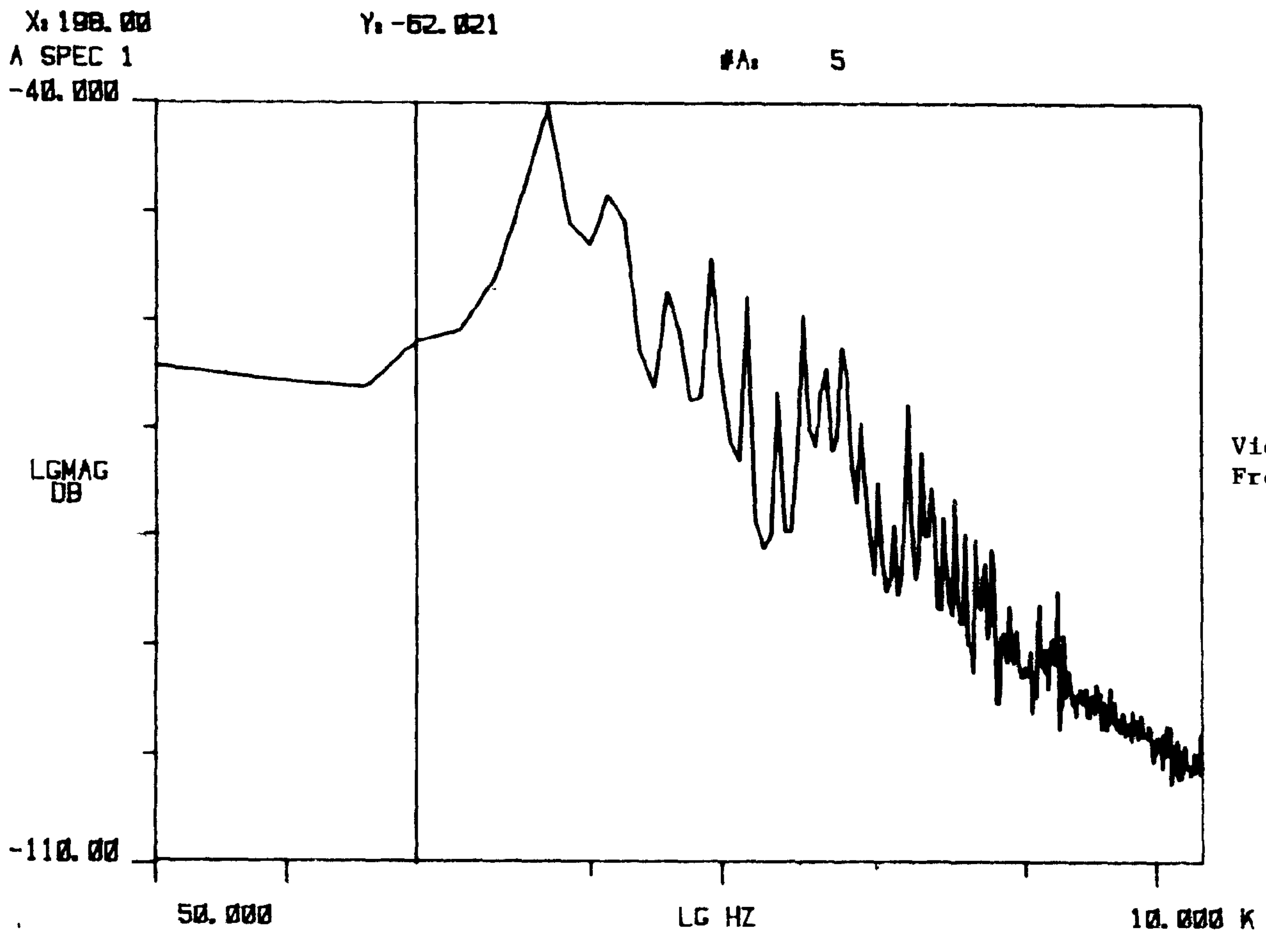
Violin Placement (7) :
Frequency Domain Analysis.



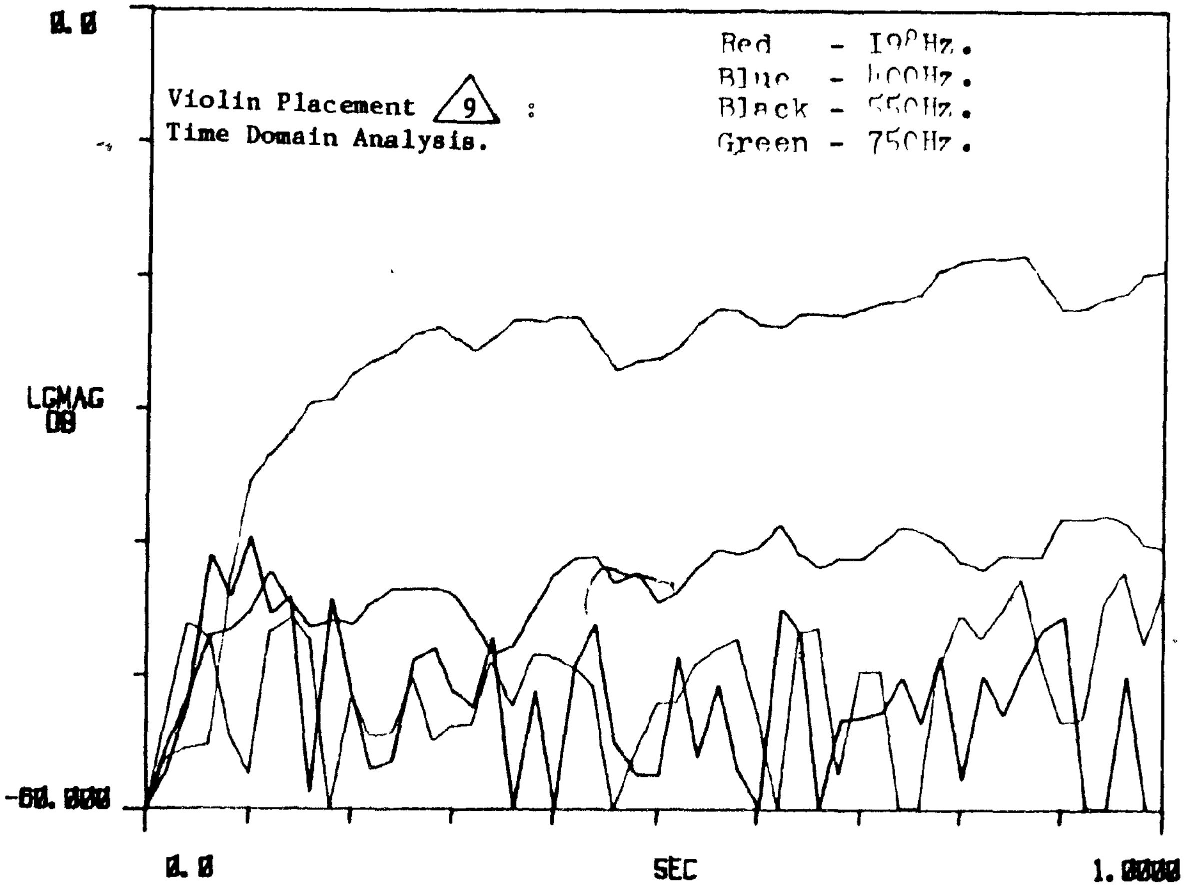
Violin Placement (8) :
Frequency Domain Analysis.

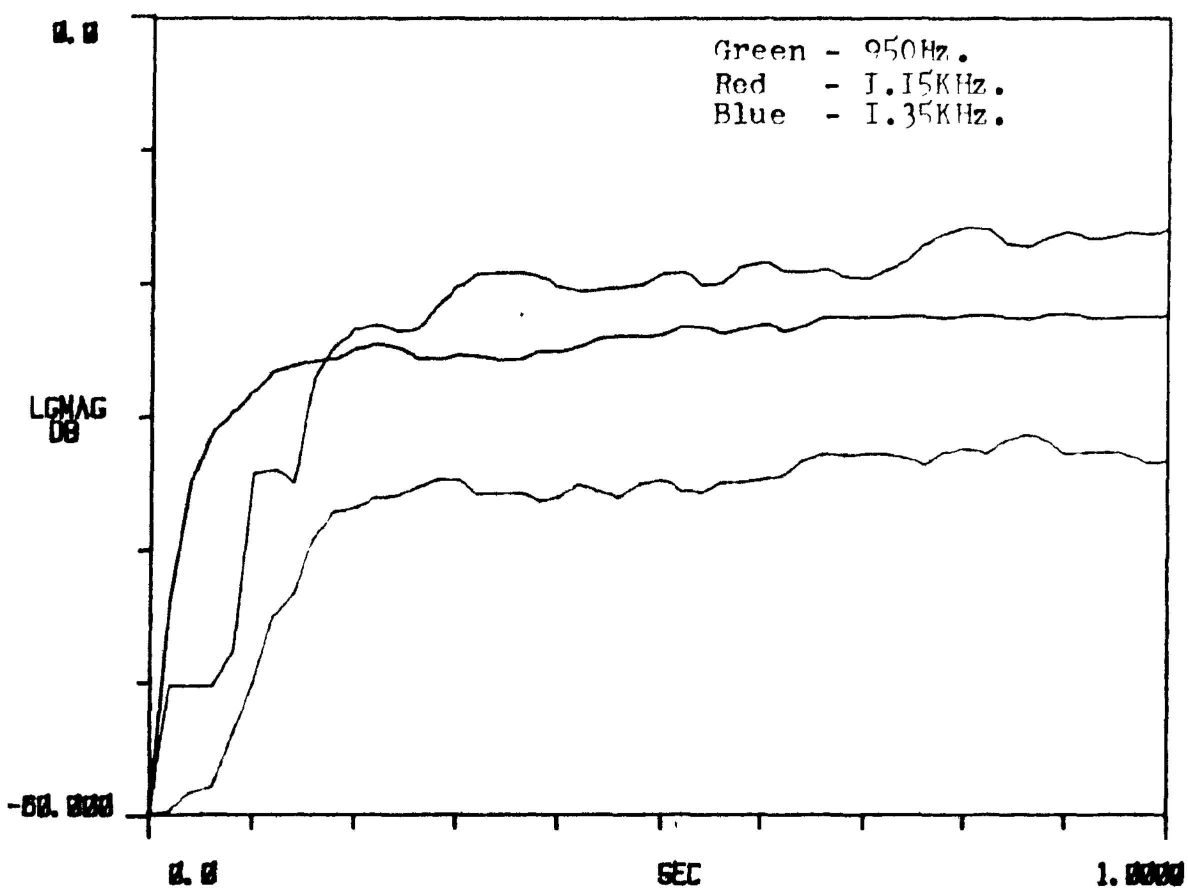

Violin Placement 8 :
Time Domain Analysis.
Black - 198Hz.
Red - 400Hz.
Green - 600Hz.
Blue - 750Hz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000


Blue - 950Hz.
Black - 1.15KHz.
Red - 1.35KHz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000



Violin Placement 9 :
Frequency Domain Analysis.

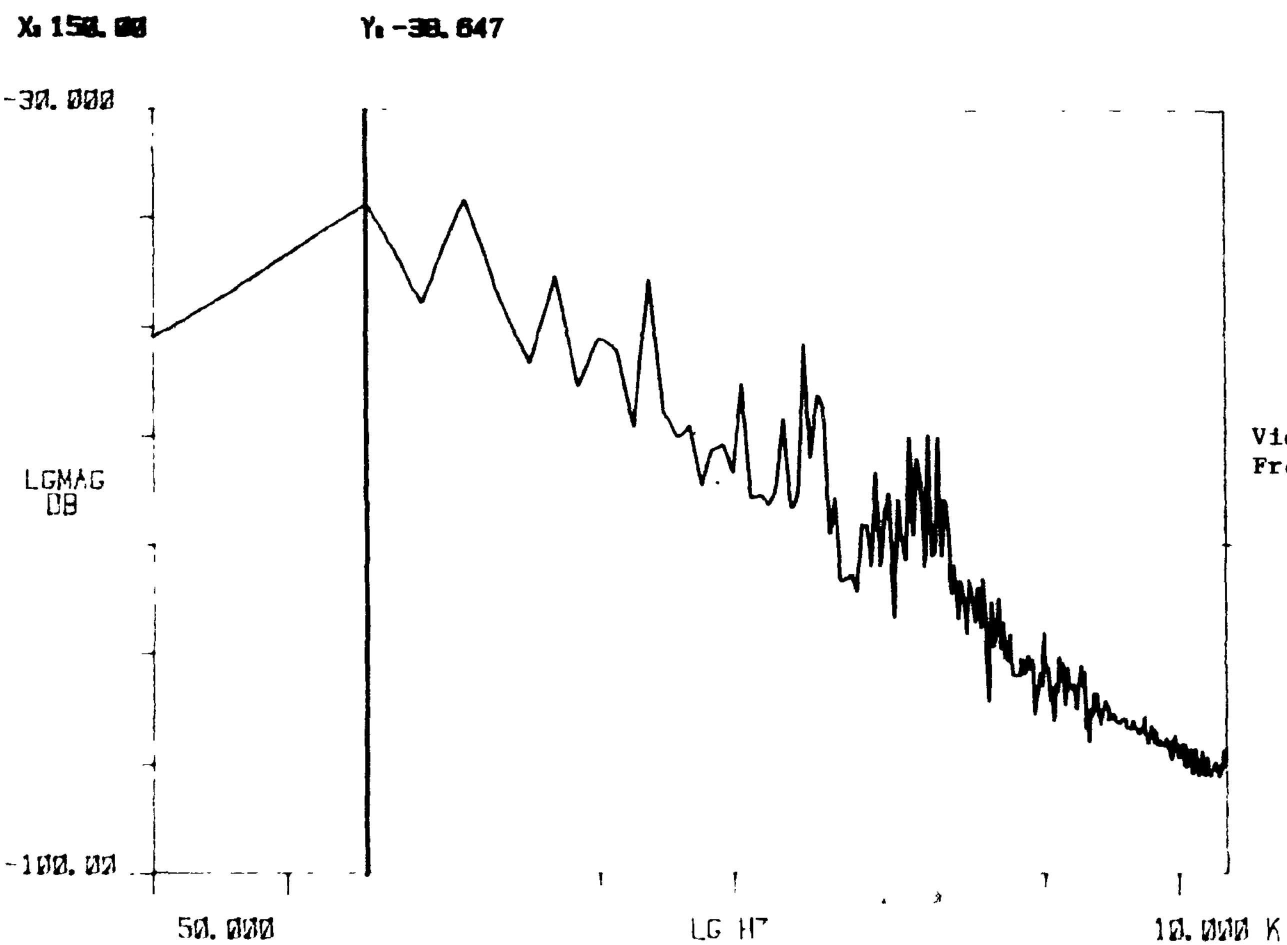

Violin Placement 9 :
Time Domain Analysis.
Red - 198Hz.
Blue - 600Hz.
Black - 550Hz.
Green - 750Hz.
0.0
LGMAG
DB
-80.000
0.0
SEC
1.0000


Green - 950Hz.
Red - 1.15KHz.
Blue - 1.35KHz.
0.0
LGMAG
DB
-80.000
0.0
SEC
1.0000

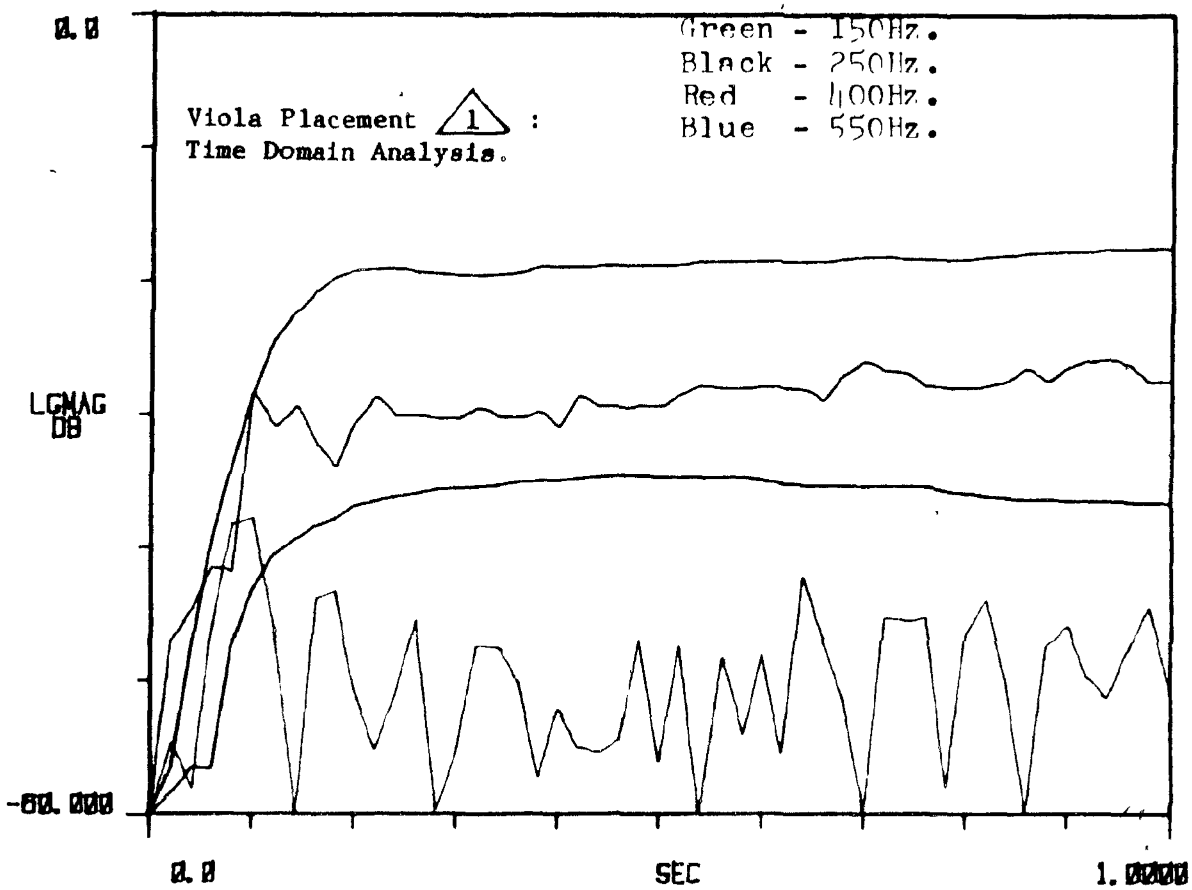
APPENDIX II

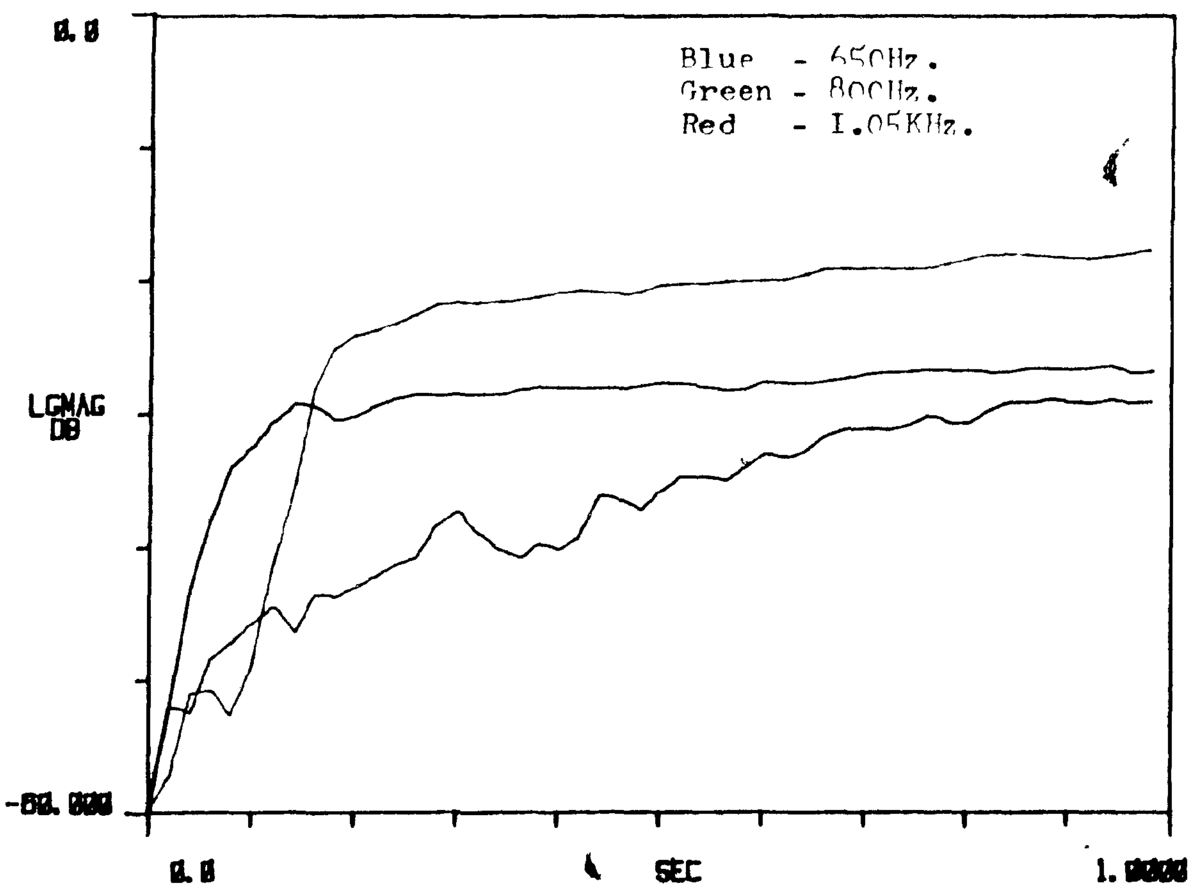
Viola

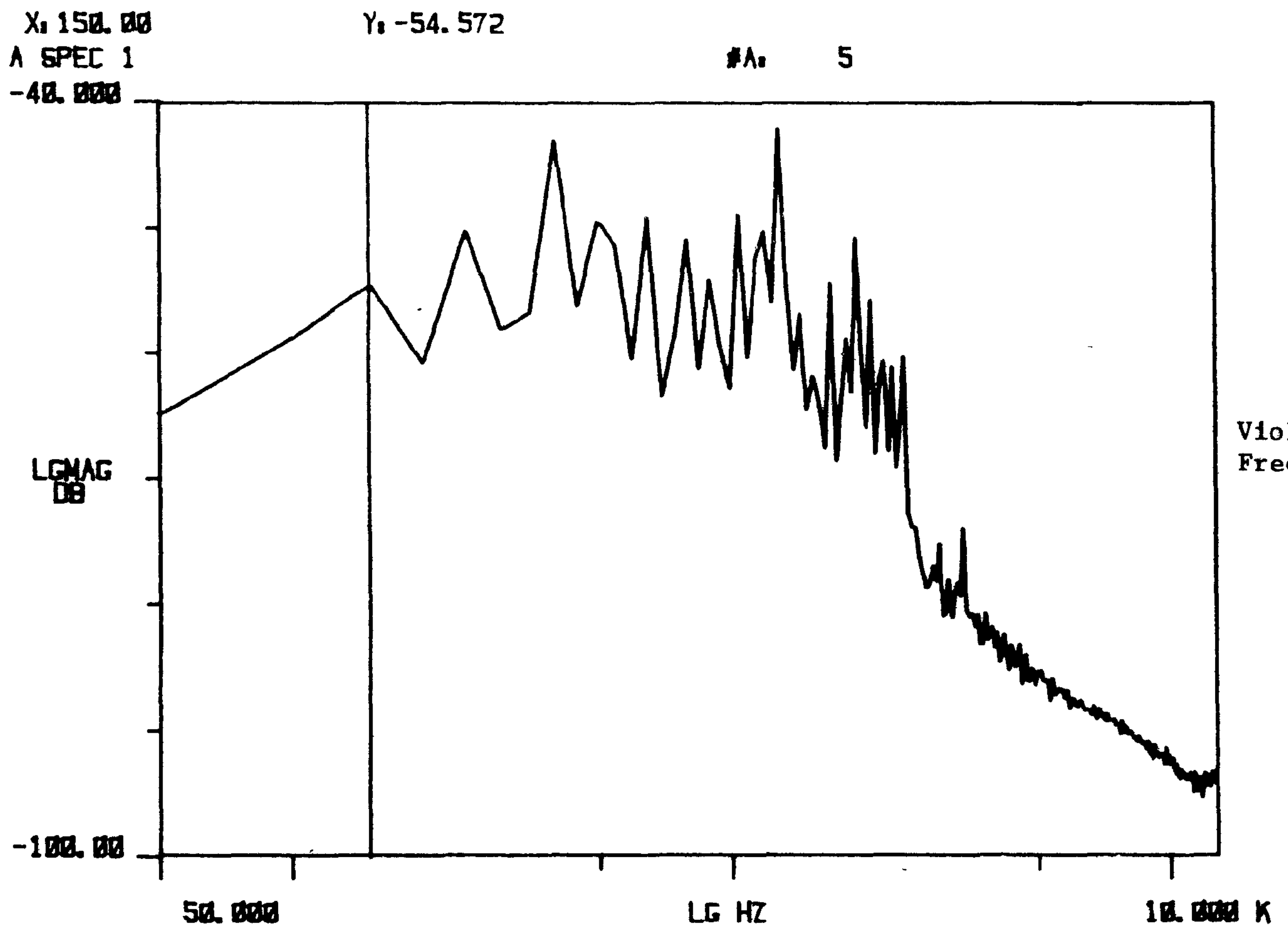
Spectrum Analysis



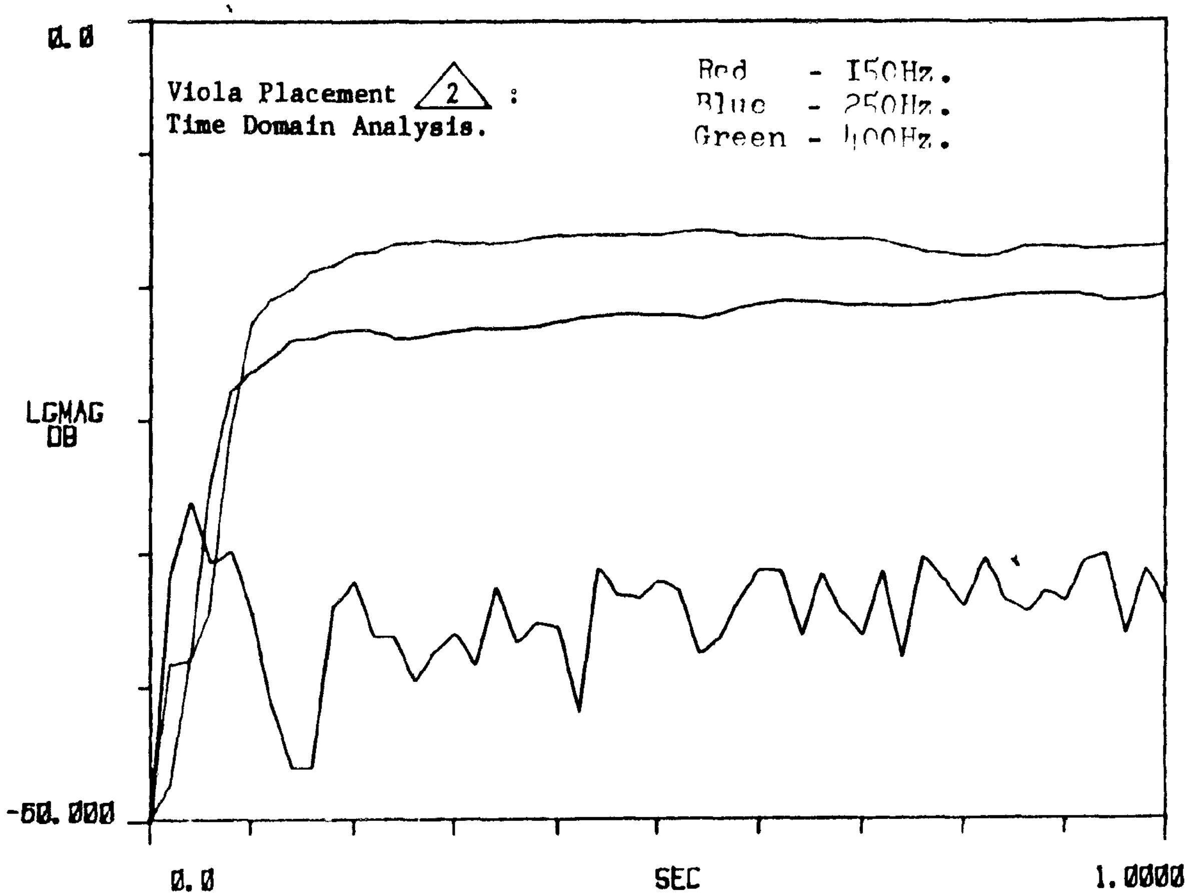
Viola Placement (1) :
Frequency Domain Analysis.


0.0
Viola Placement 1 :
Time Domain Analysis.
Green - 150Hz.
Black - 250Hz.
Red - 400Hz.
Blue - 550Hz.
LGMAG DB
-80.000
0.0
SEC
1.0000

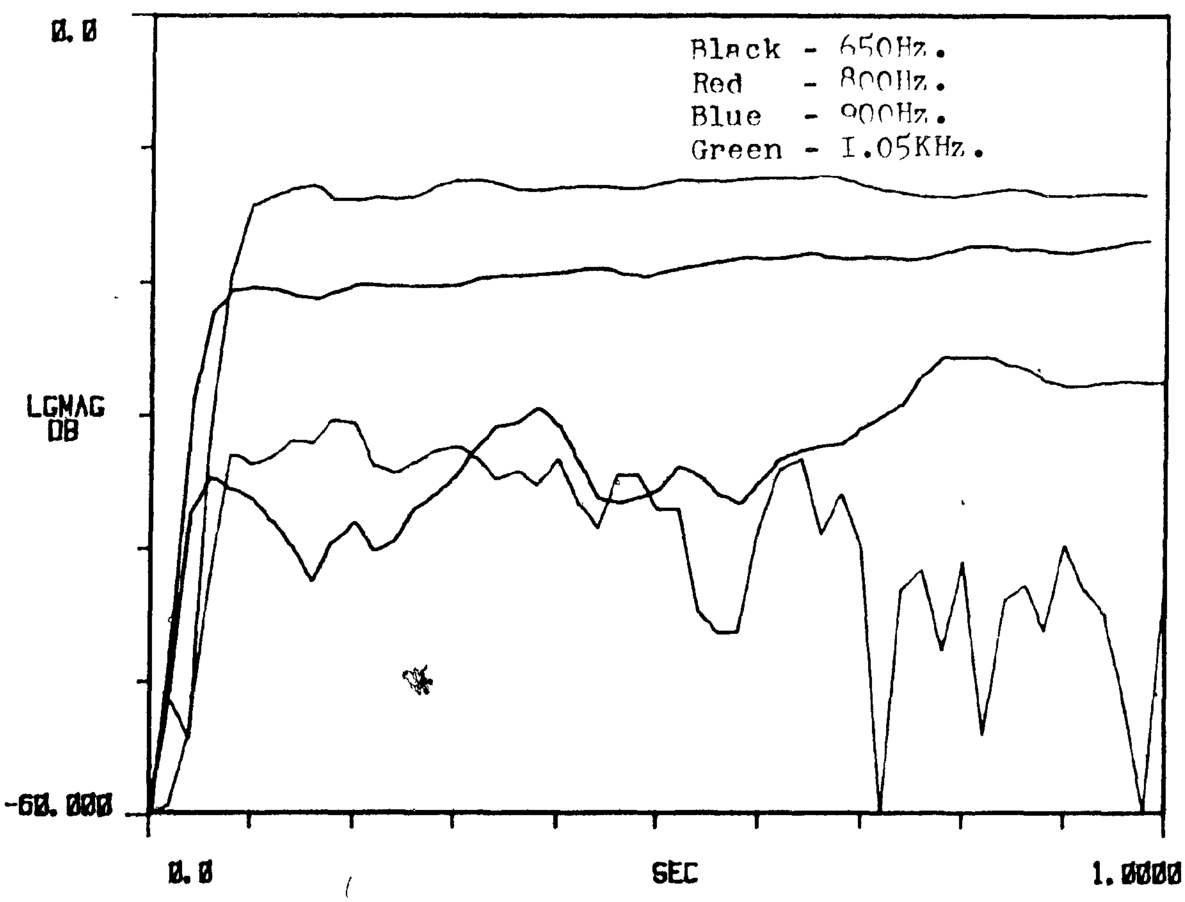

0.0
Blue - 650Hz.
Green - 800Hz.
Red - 1.05KHz.
LGMAG DB
-80.000
0.0
SEC
1.0000



Viola Placement (2) :
Frequency Domain Analysis.

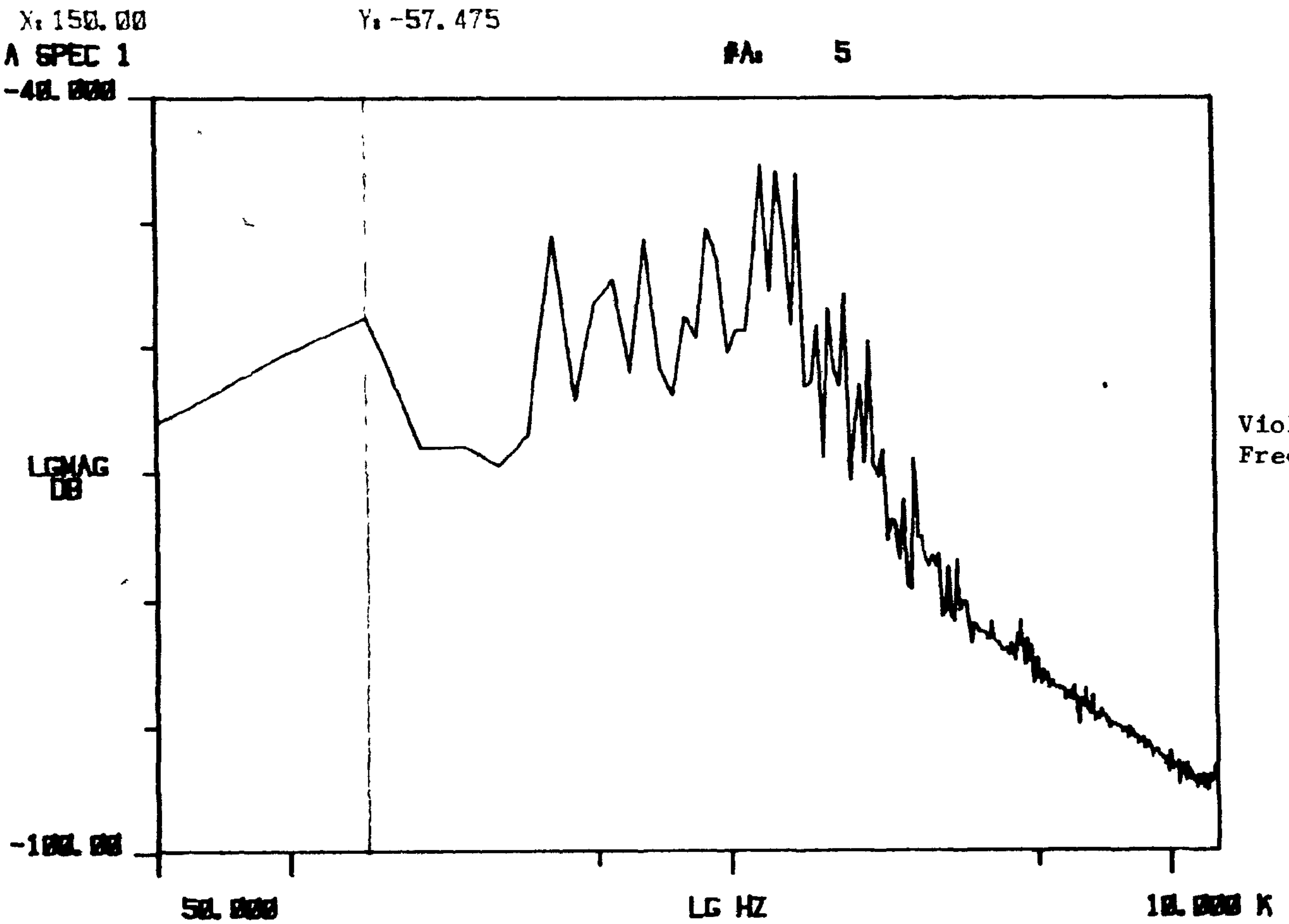


0.0
Viola Placement 2 :
Time Domain Analysis.
Red - 150Hz.
Blue - 250Hz.
Green - 400Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

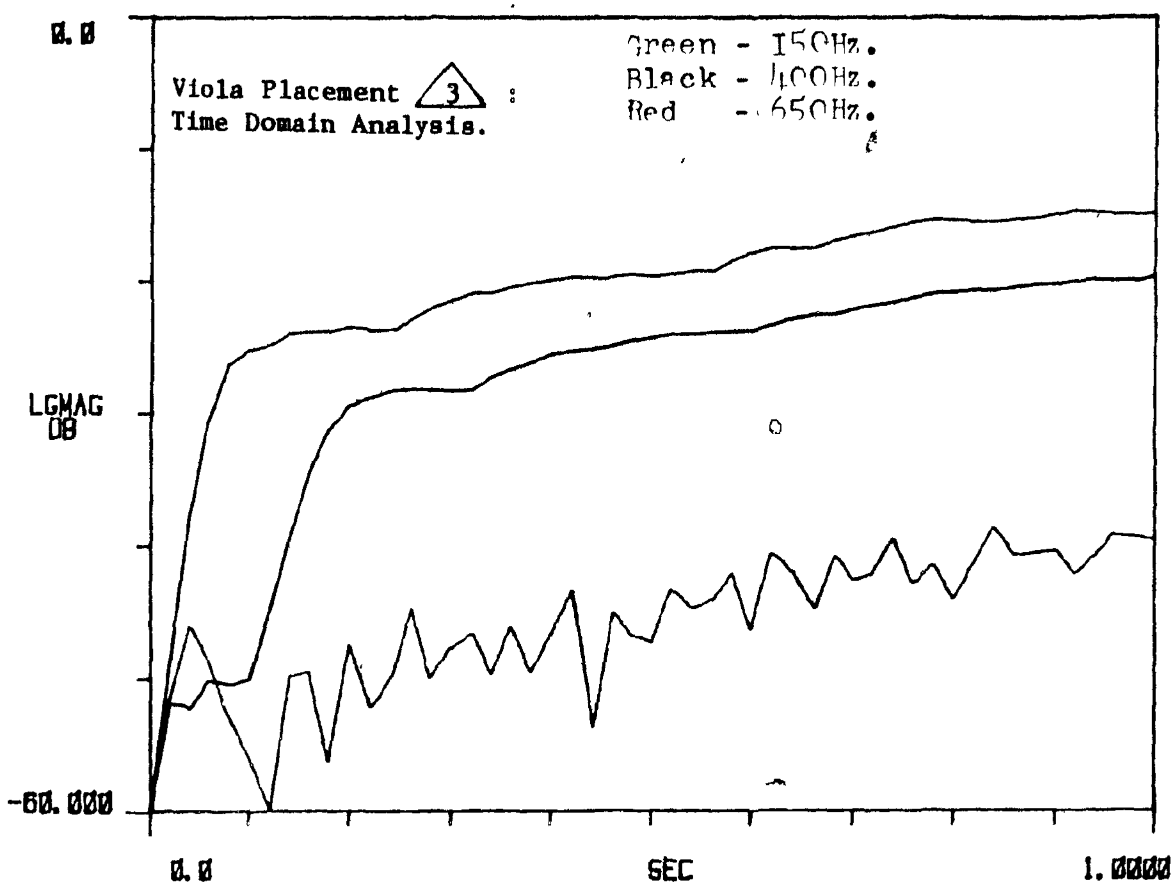


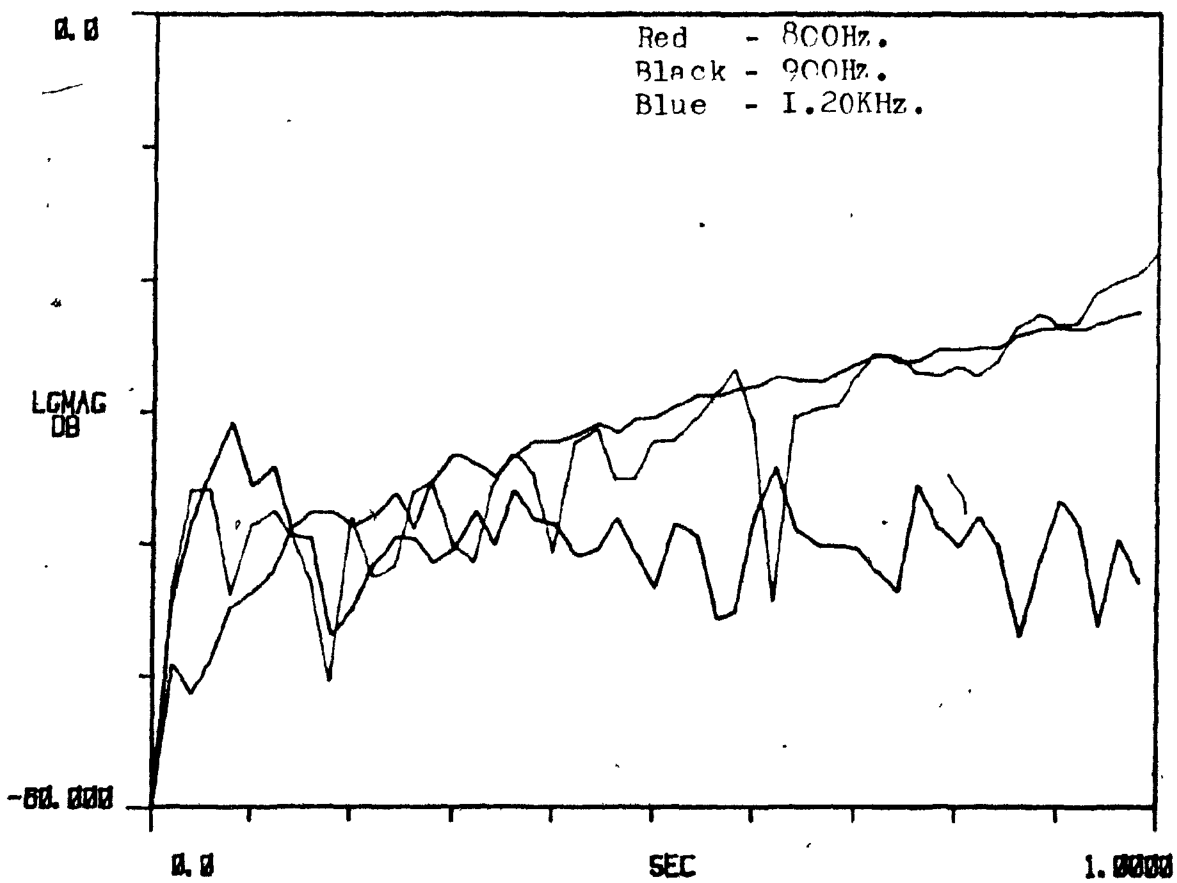
0.0
Black - 650Hz.
Red - 800Hz.
Blue - 900Hz.
Green - 1.05KHz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

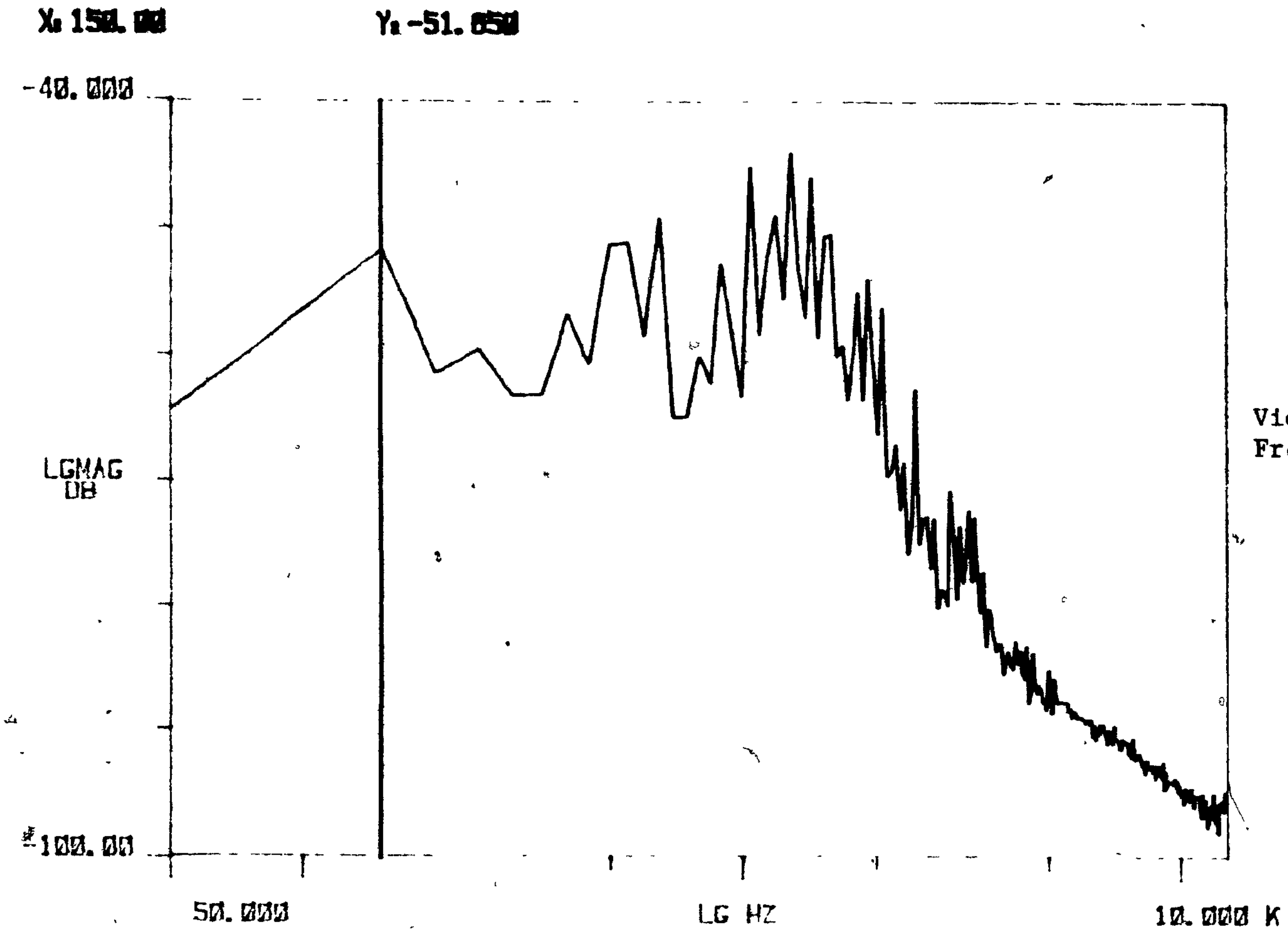
140



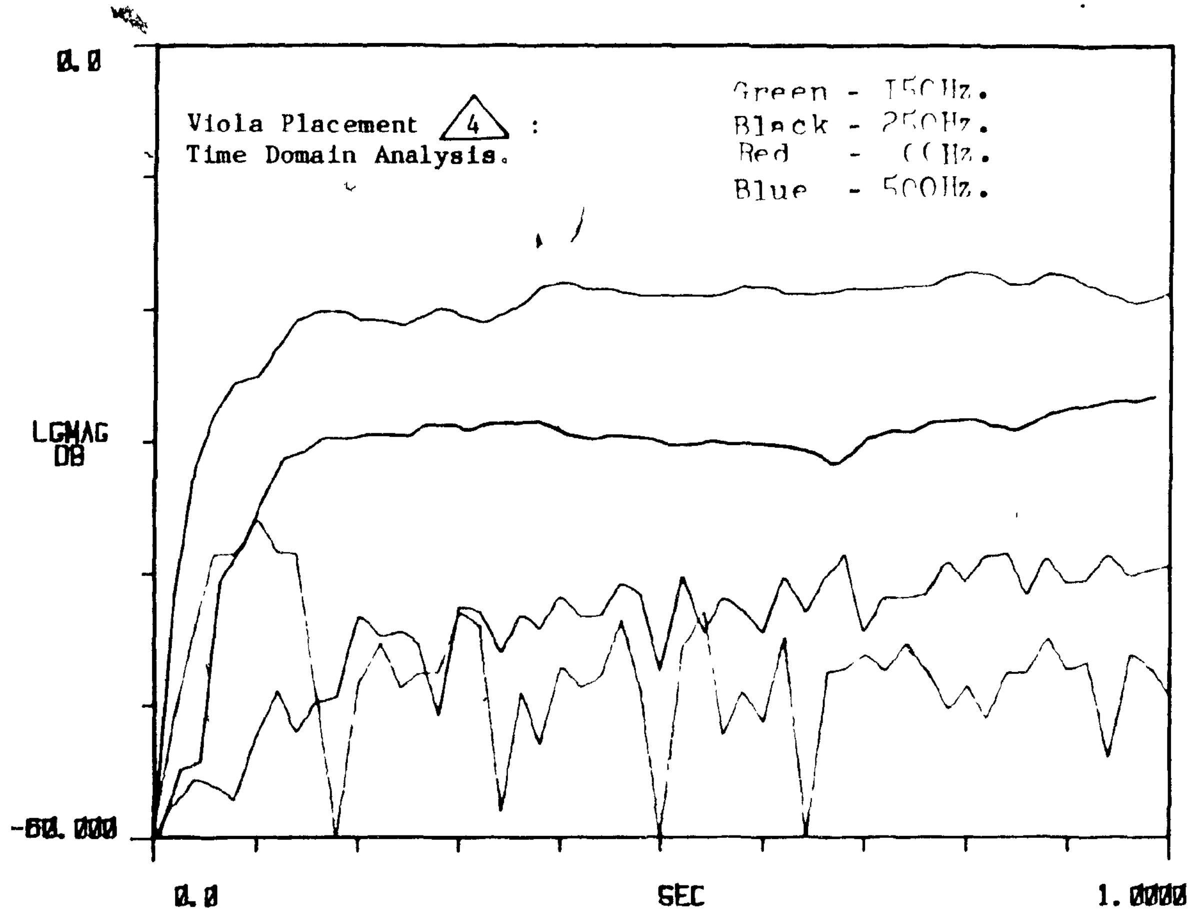
Viola Placement △3 :
Frequency Domain Analysis.

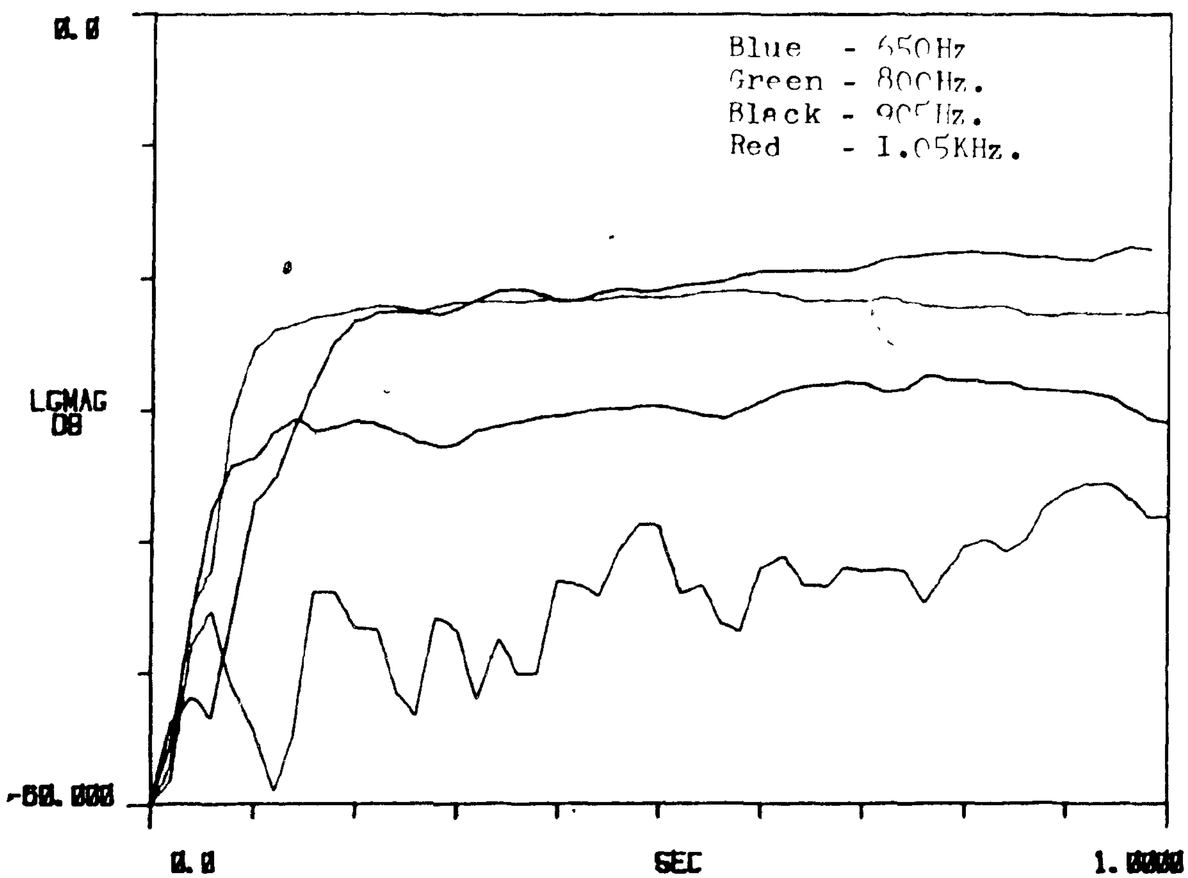

Viola Placement 3 :
Time Domain Analysis.
Green - 150Hz.
Black - 400Hz.
Red - 650Hz.
0.0
LGMAG DB
-60.000
0.0
SEC
1.0000

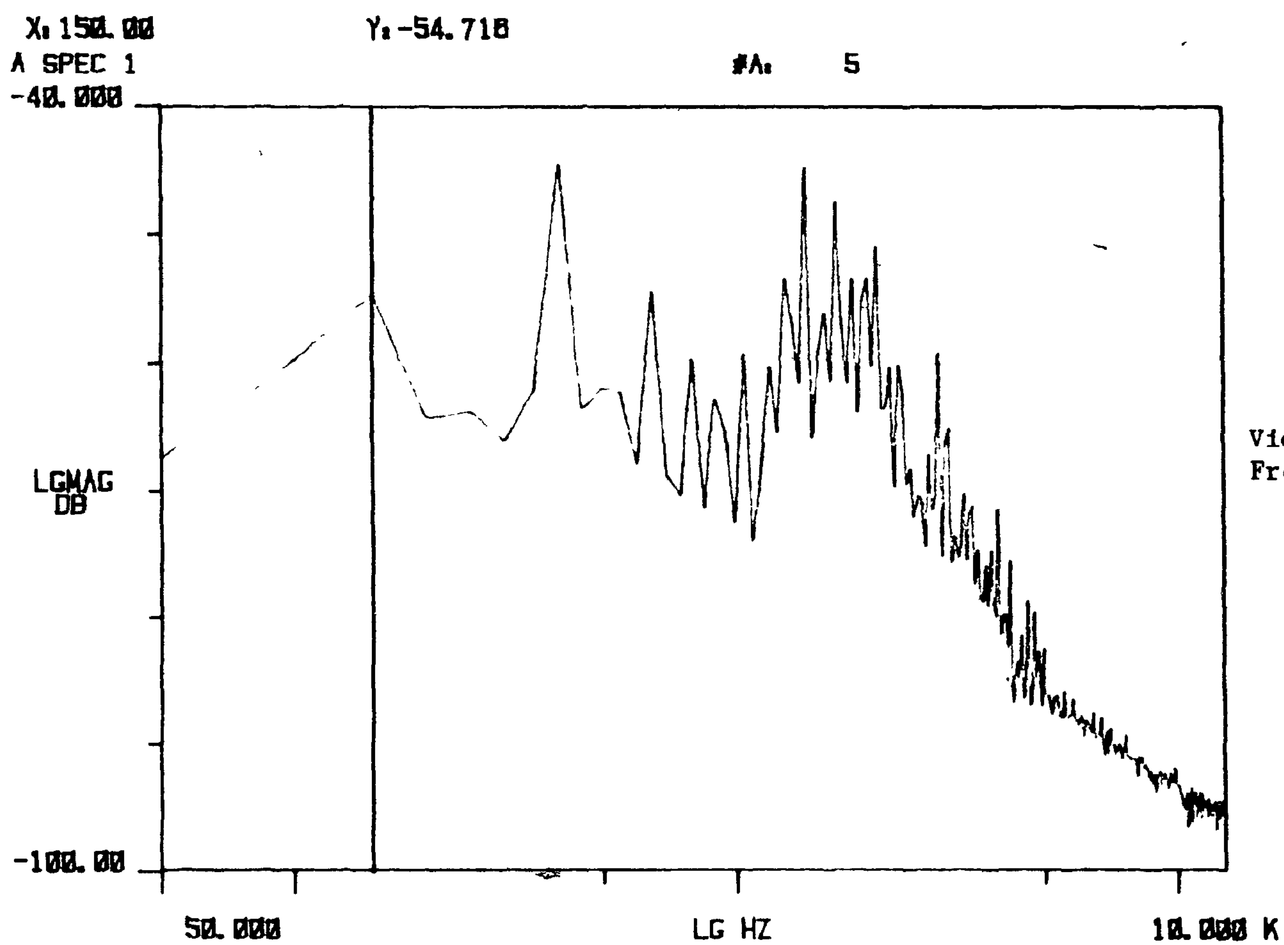

Red - 800Hz.
Black - 900Hz.
Blue - 1.20KHz.
0.0
LGMAG DB
-60.000
0.0
SEC
1.0000



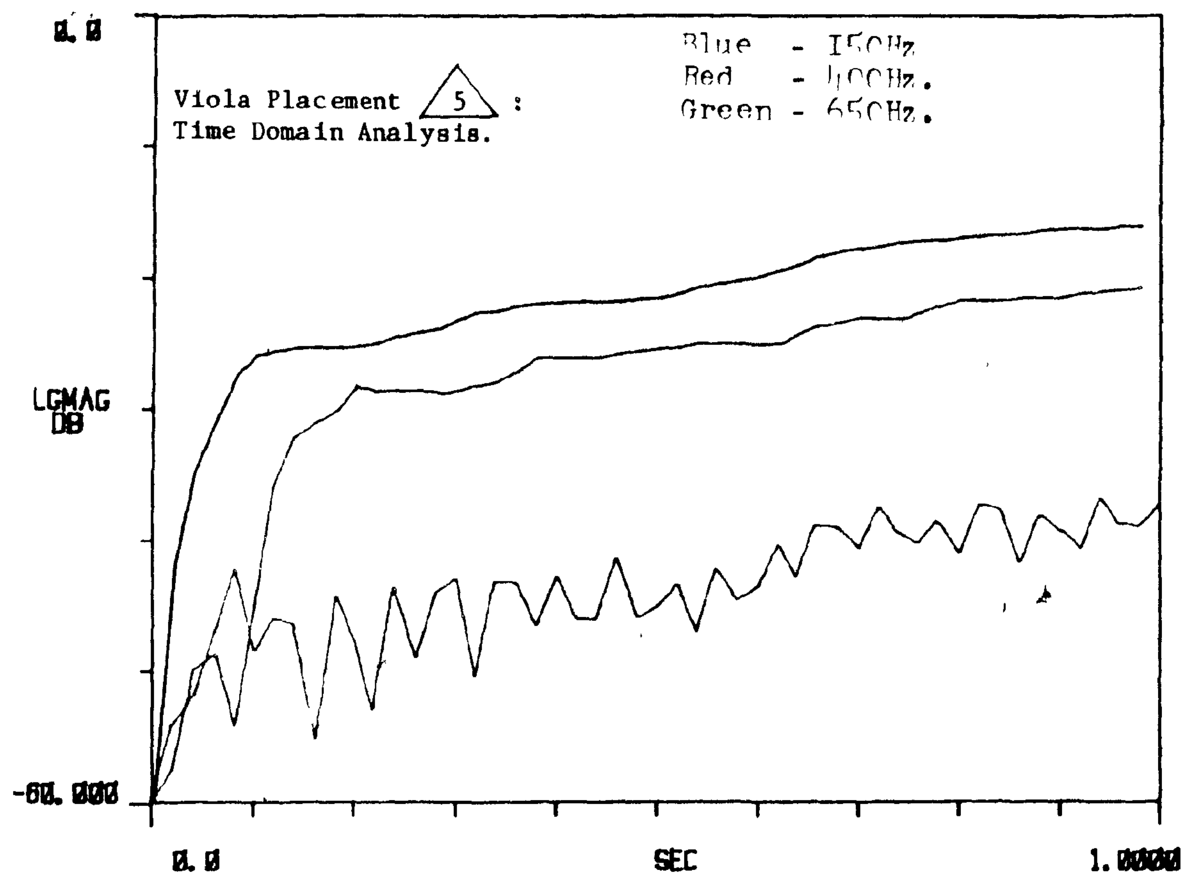
Viola Placement △4 : Frequency Domain Analysis.

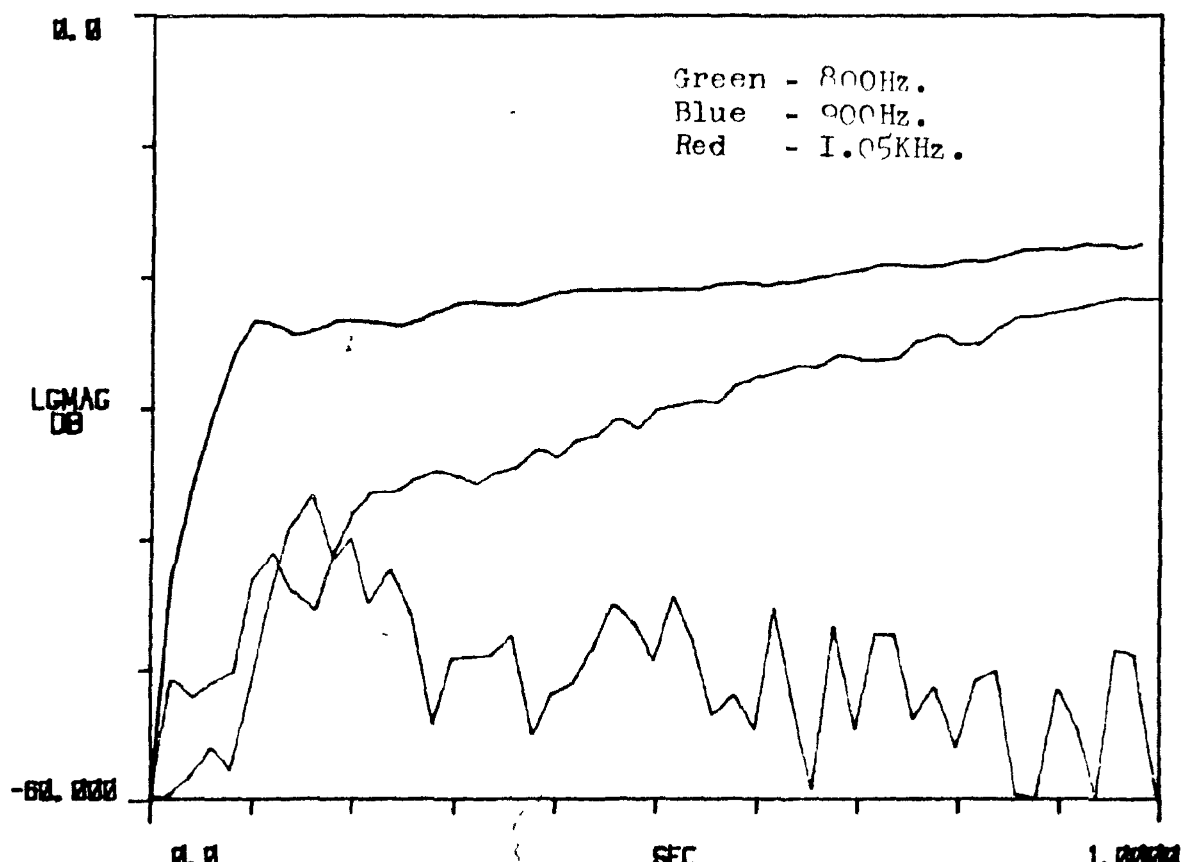

Viola Placement 4 :
Time Domain Analysis.
Green - 150Hz.
Black - 250Hz.
Red -
Blue - 500Hz.
0.0
LGMAG
DB
-80.000
0.0
SEC
1.0000

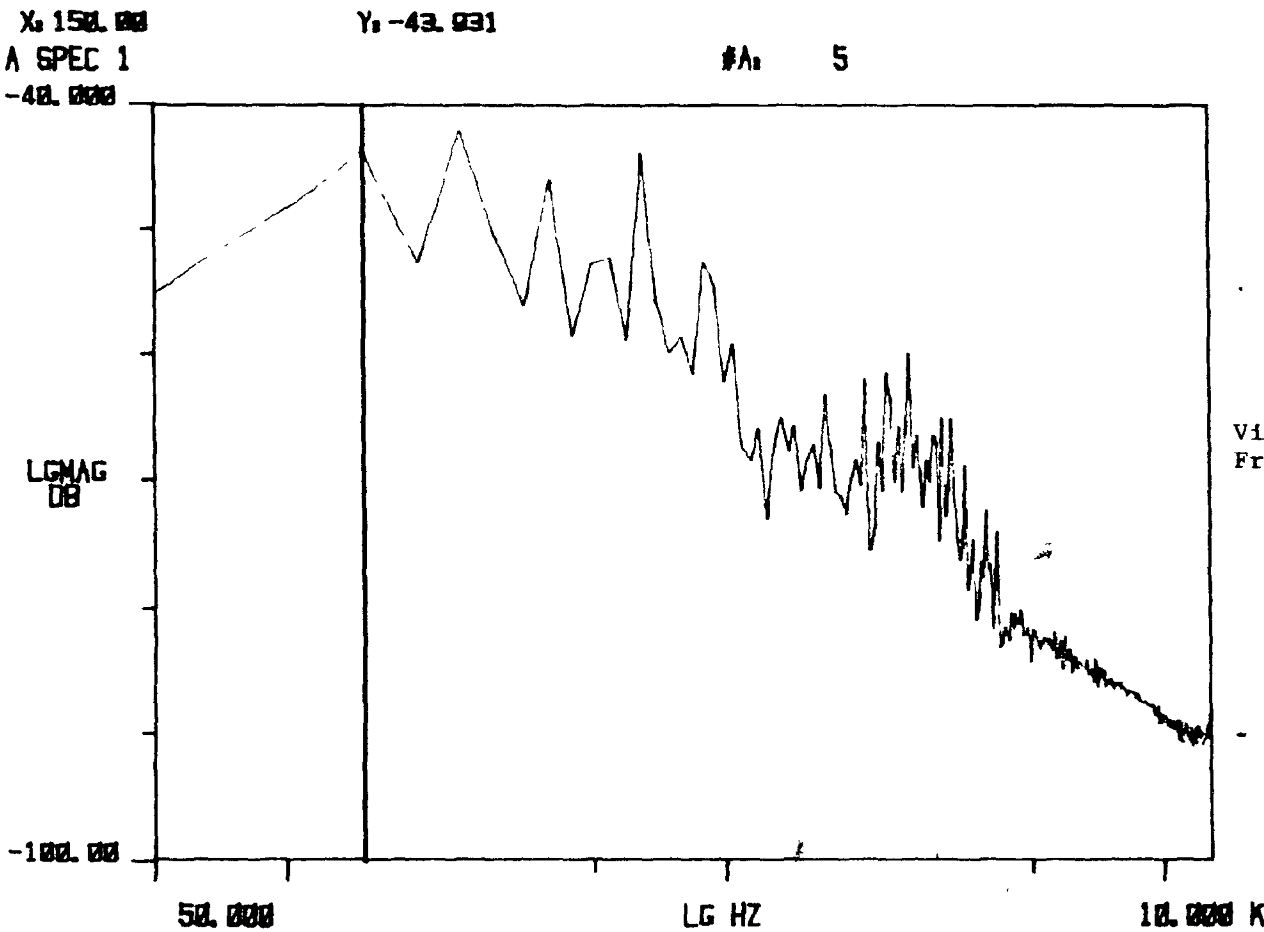

Blue - 650Hz
Green - 800Hz.
Black -
Red - 1.05KHz.
0.0
LGMAG
DB
-80.000
0.0
SEC
1.0000



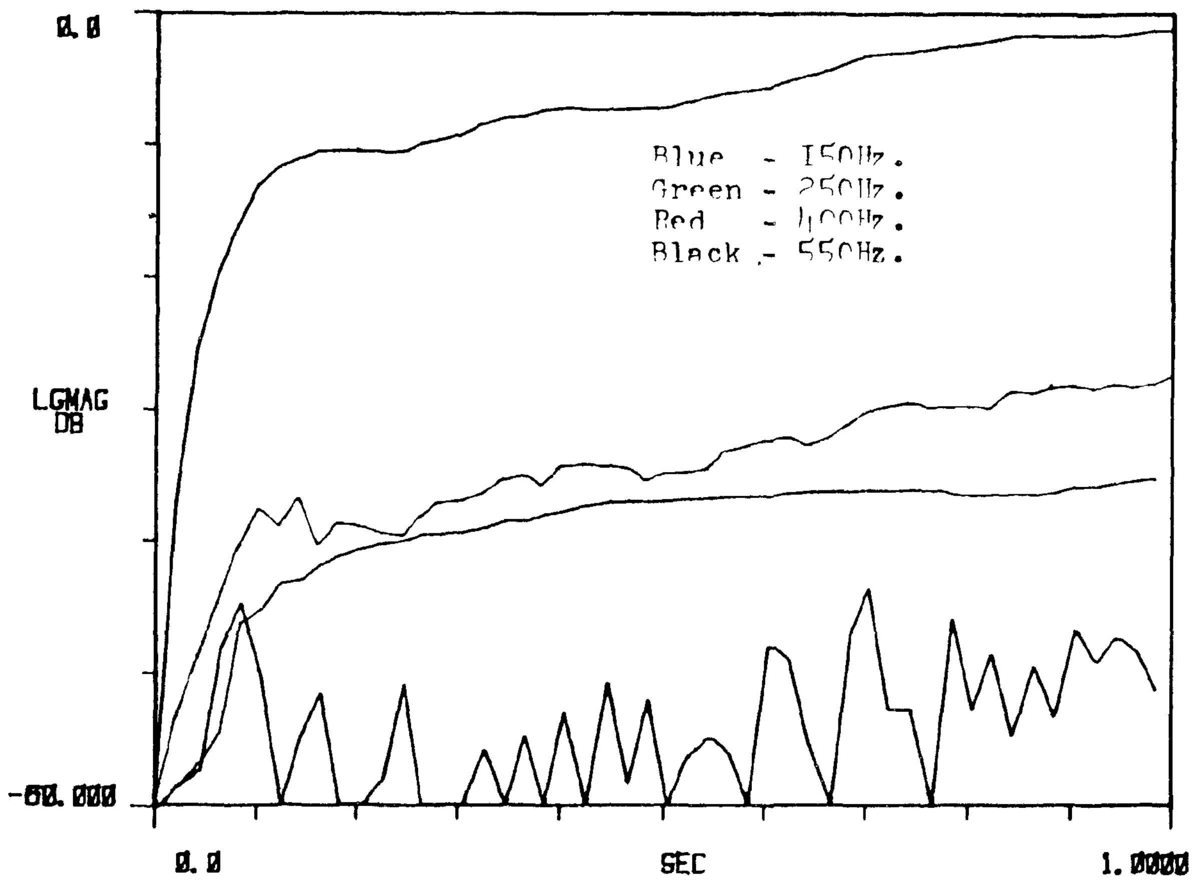
Viola Placement (5) :
Frequency Domain Analysis.

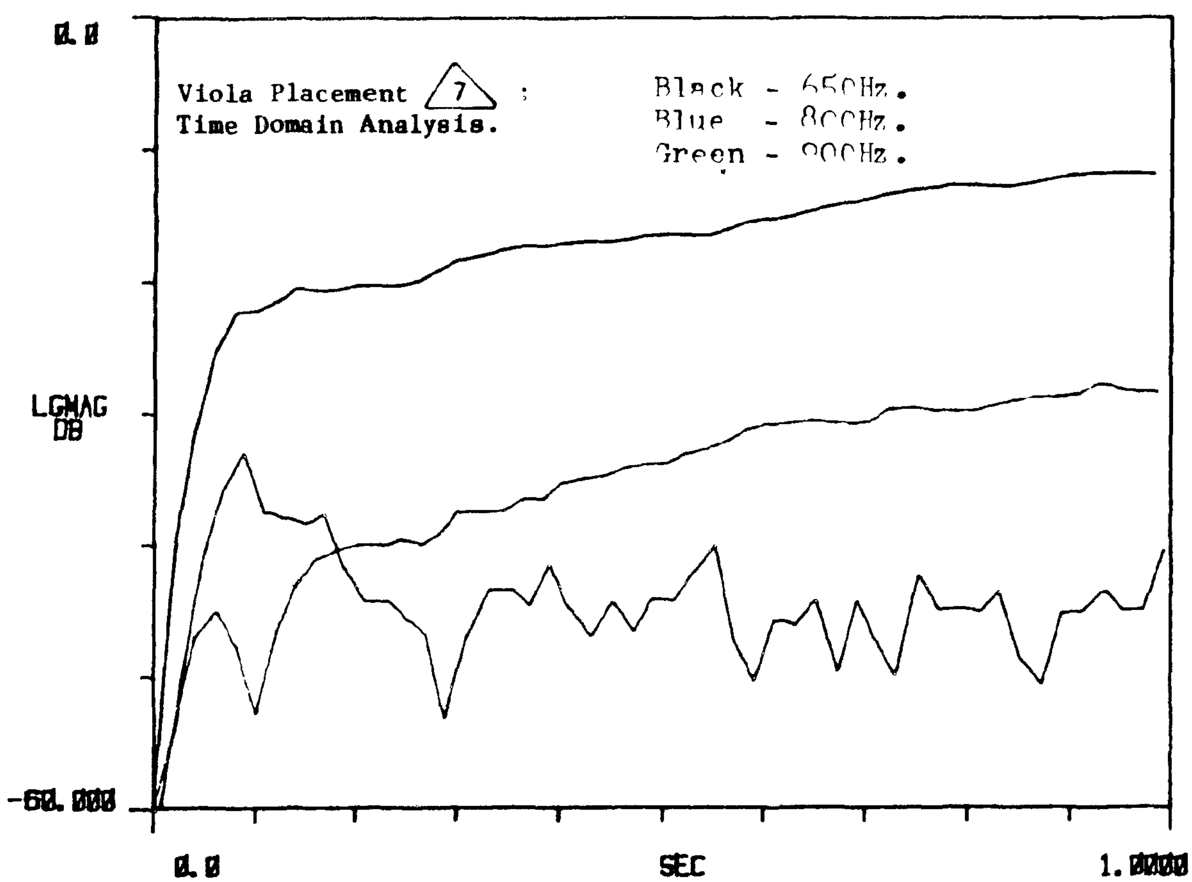

Viola Placement 5 :
Time Domain Analysis.
Blue - 150Hz
Red - 400Hz.
Green - 650Hz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000

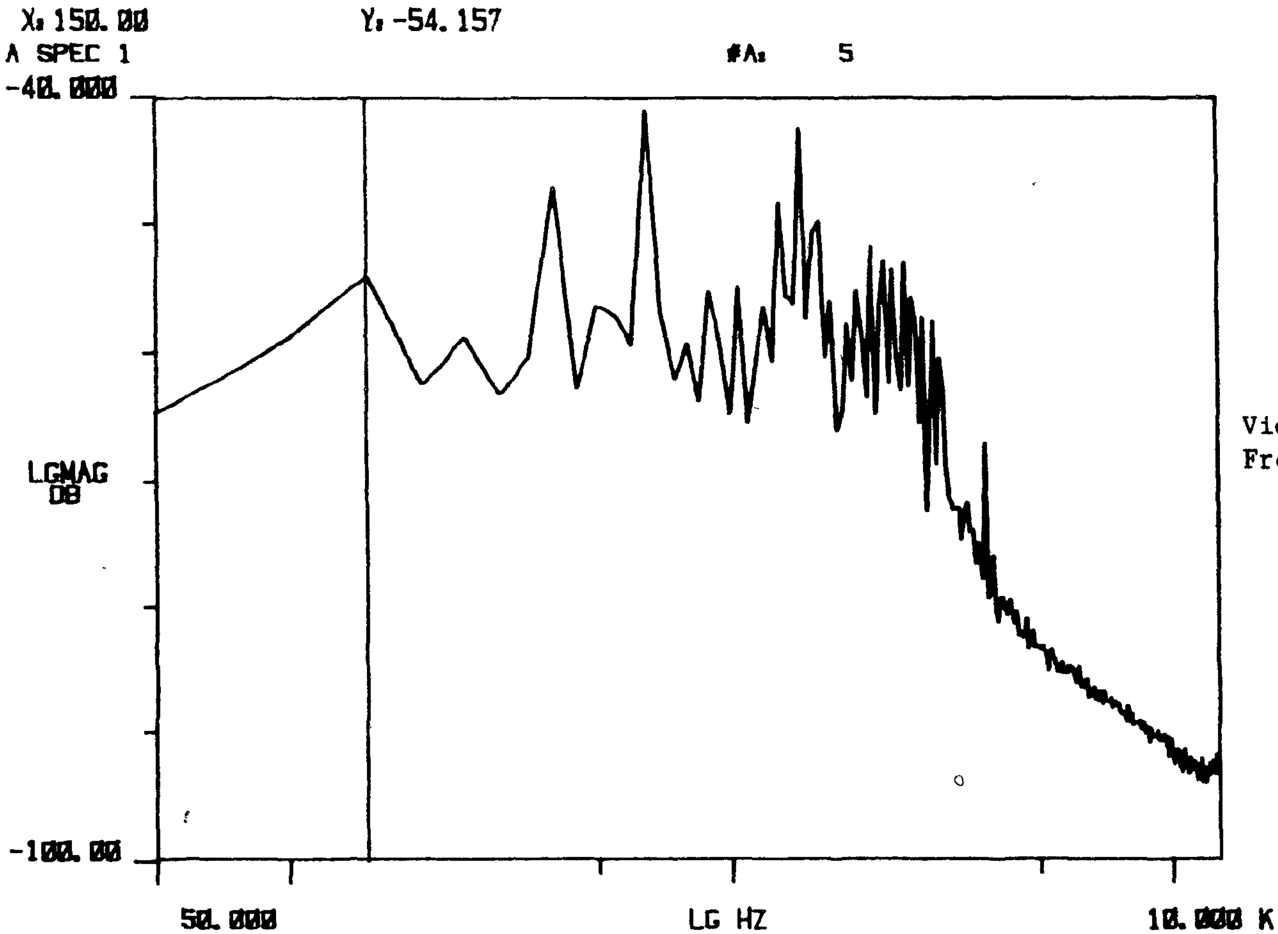

Green - 800Hz.
Blue - 900Hz.
Red - I.05KHz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000



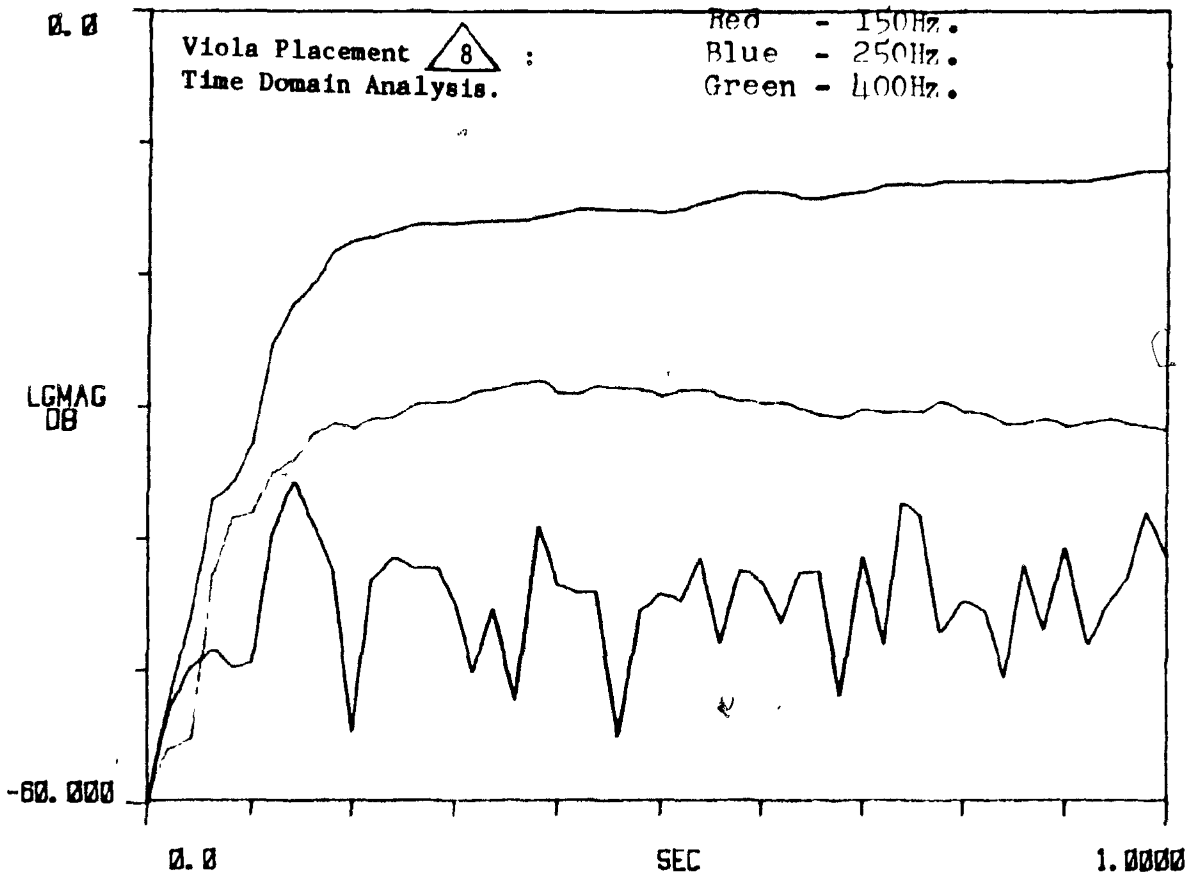
Viola Placement 7 :
Frequency Domain Analysis.


0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Blue - 150Hz.
Green - 250Hz.
Red - 400Hz.
Black - 550Hz.

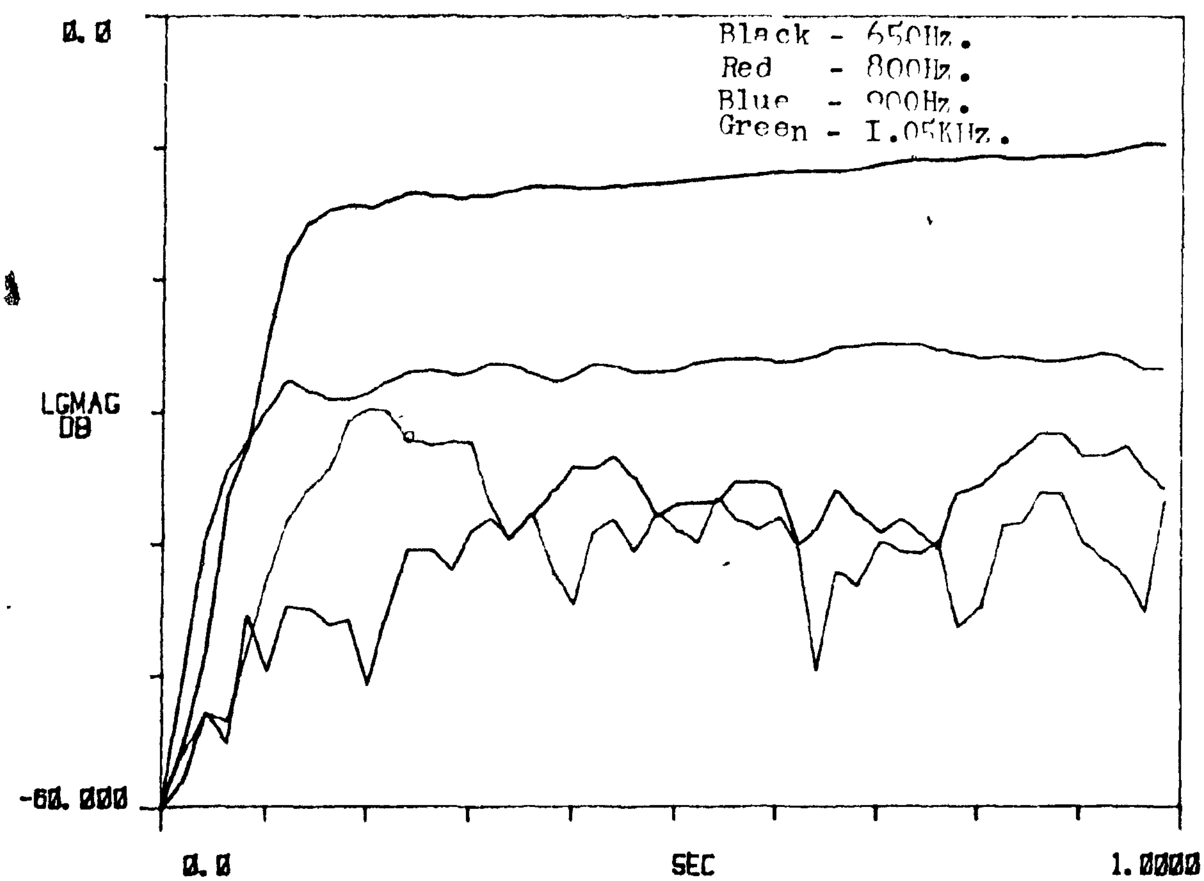

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Viola Placement 7 :
Time Domain Analysis.
Black - 650Hz.
Blue - 800Hz.
Green - 900Hz.



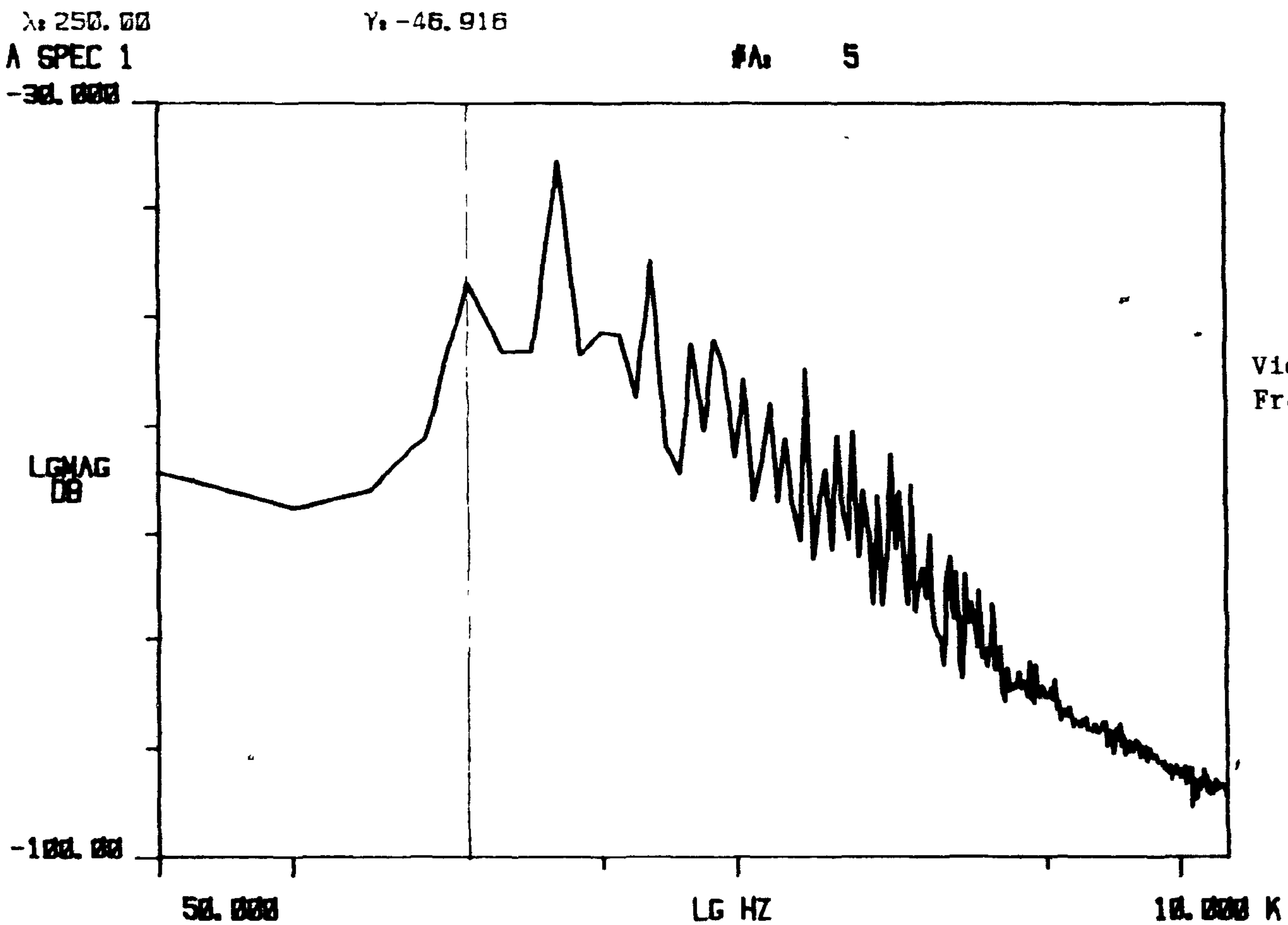
Viola Placement 8 :
Frequency Domain Analysis.



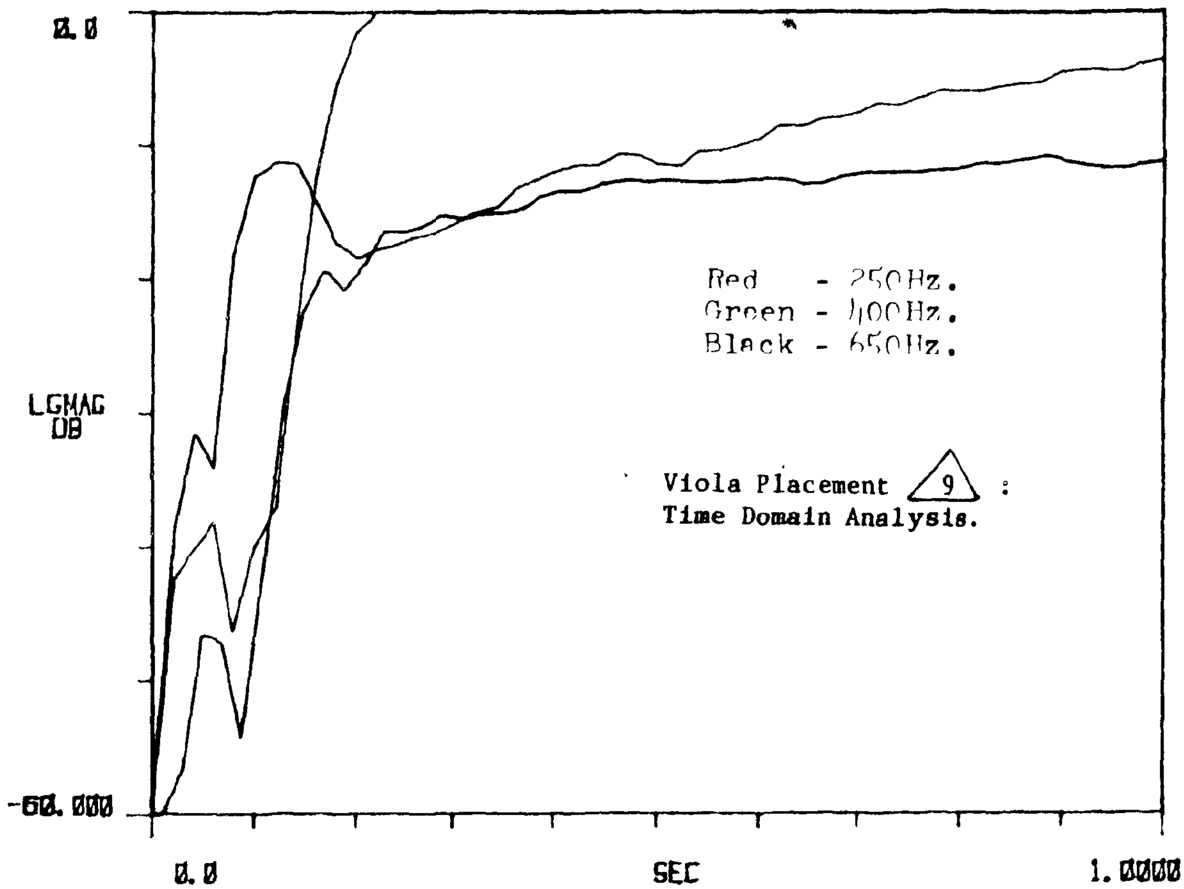
Viola Placement 8 :
Time Domain Analysis.
Red - 150Hz.
Blue - 250Hz.
Green - 400Hz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000

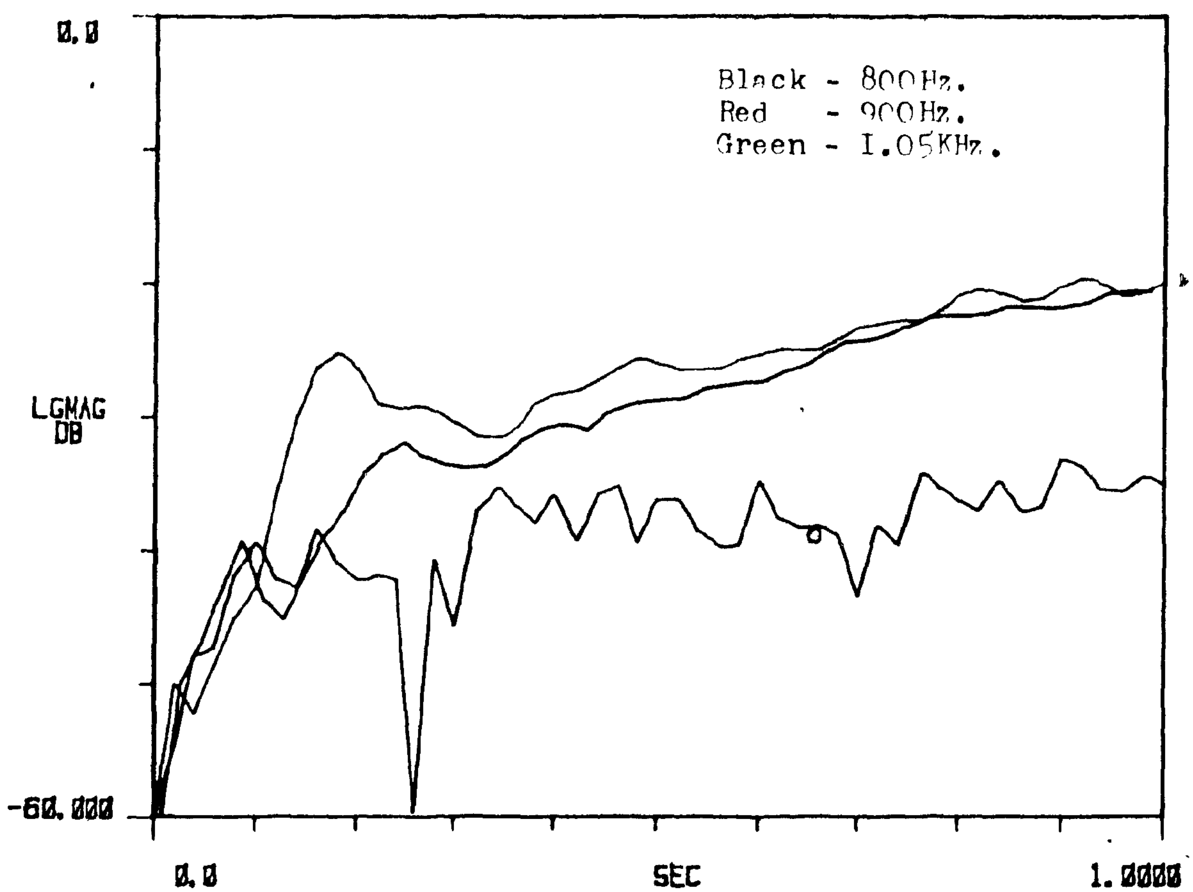


Black - 650Hz.
Red - 800Hz.
Blue - 900Hz.
Green - 1.05KHz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000



Viola Placement (9) :
Frequency Domain Analysis.

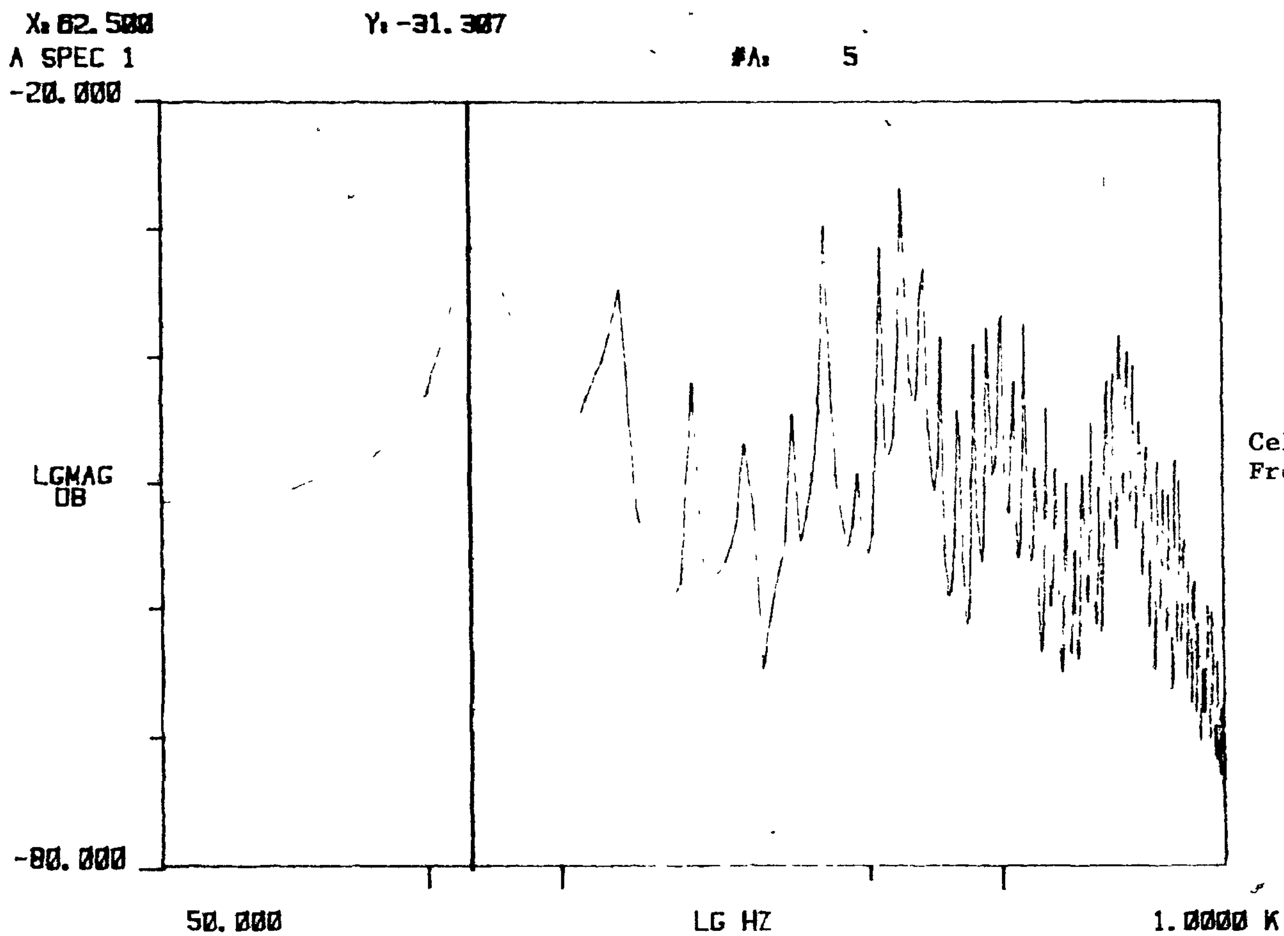

0.0
LGMAG DB
-60.000
0.0
SEC
1.0000
Red - 250Hz.
Green - 400Hz.
Black - 650Hz.
Viola Placement 9 :
Time Domain Analysis.


0.0
LGMAG DB
-60.000
0.0
SEC
1.0000
Black - 800Hz.
Red - 900Hz.
Green - 1.05KHz.

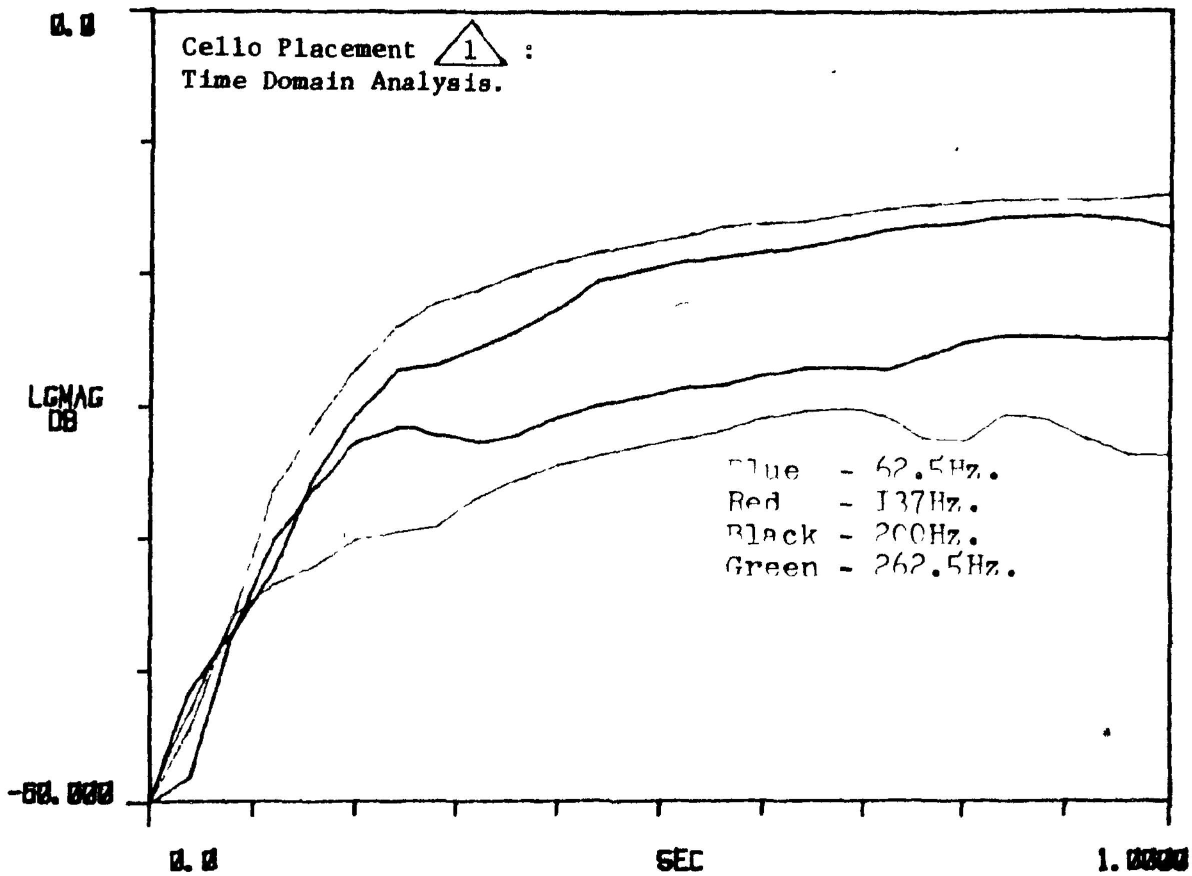
APPENDIX III

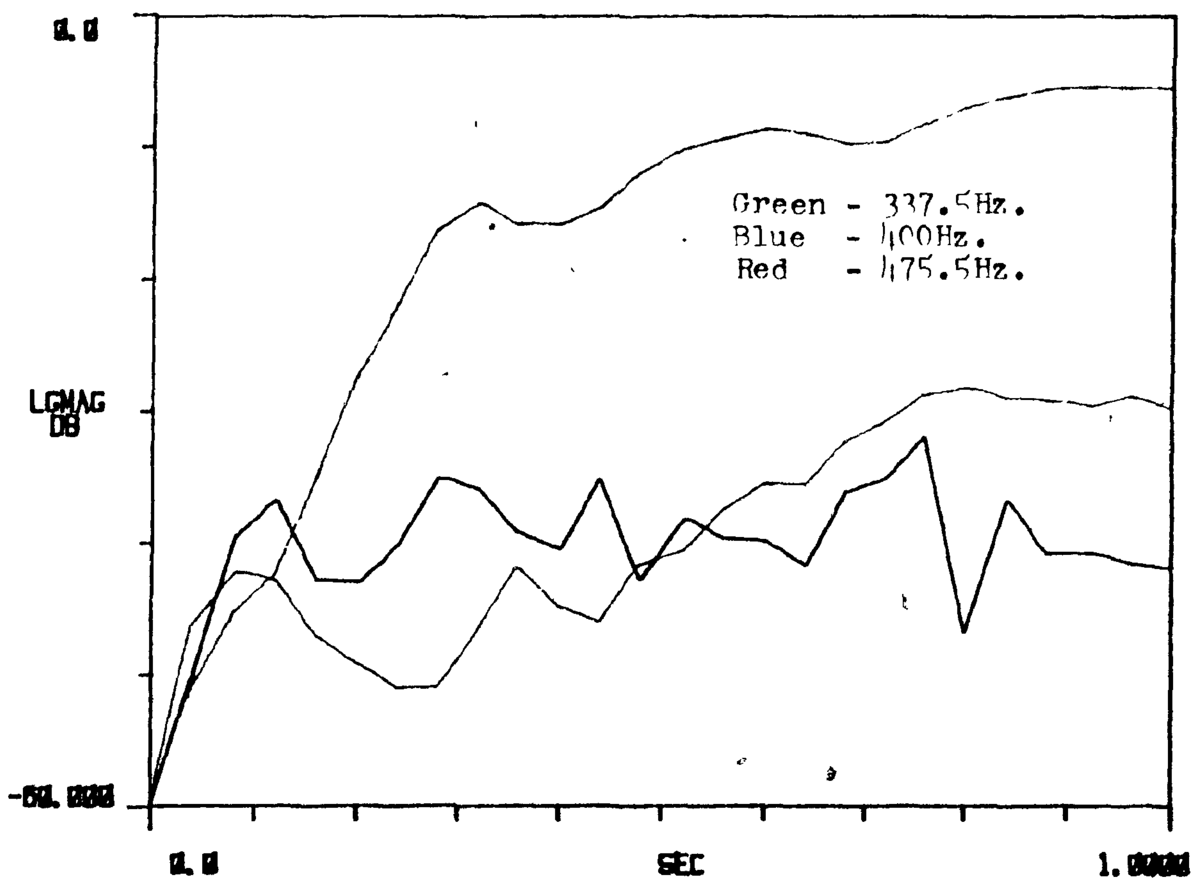
Cello

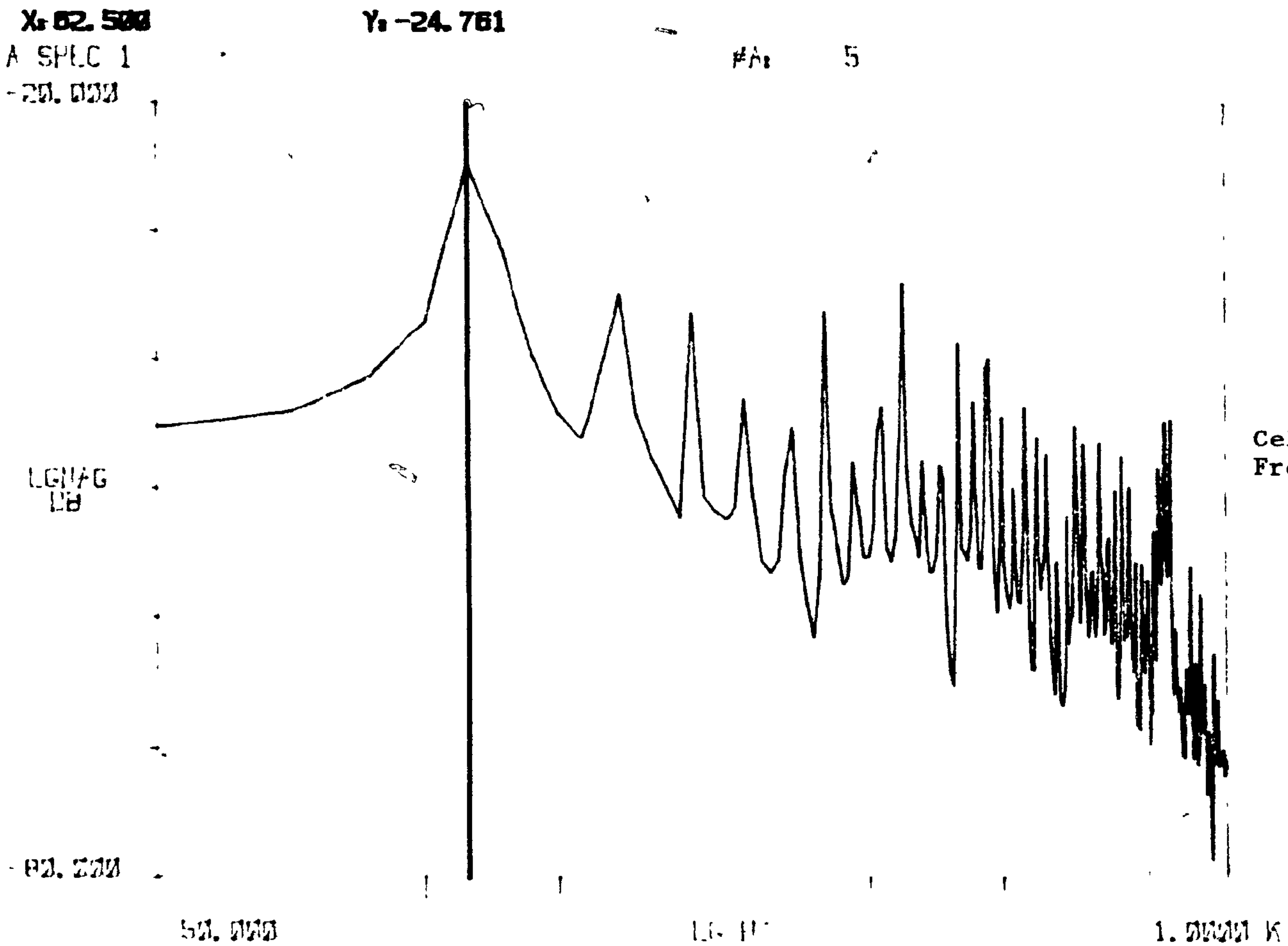
Spectrum Analysis



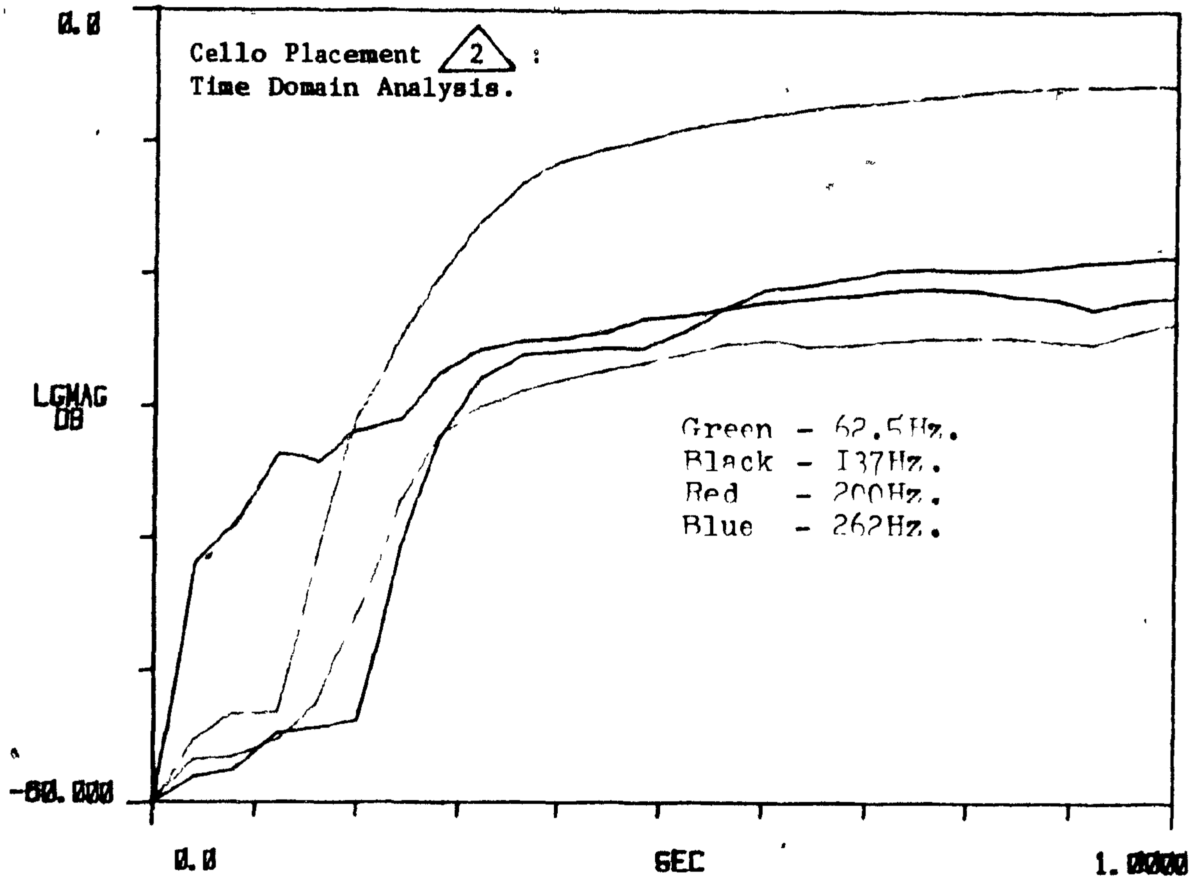
Cello Placement (1) :
Frequency Domain Analysis.


Cello Placement 1 :
Time Domain Analysis.
0.0
LGMAG
DB
-60.000
Blue - 62.5Hz.
Red - 137Hz.
Black - 200Hz.
Green - 262.5Hz.
0.0
SEC
1.0000

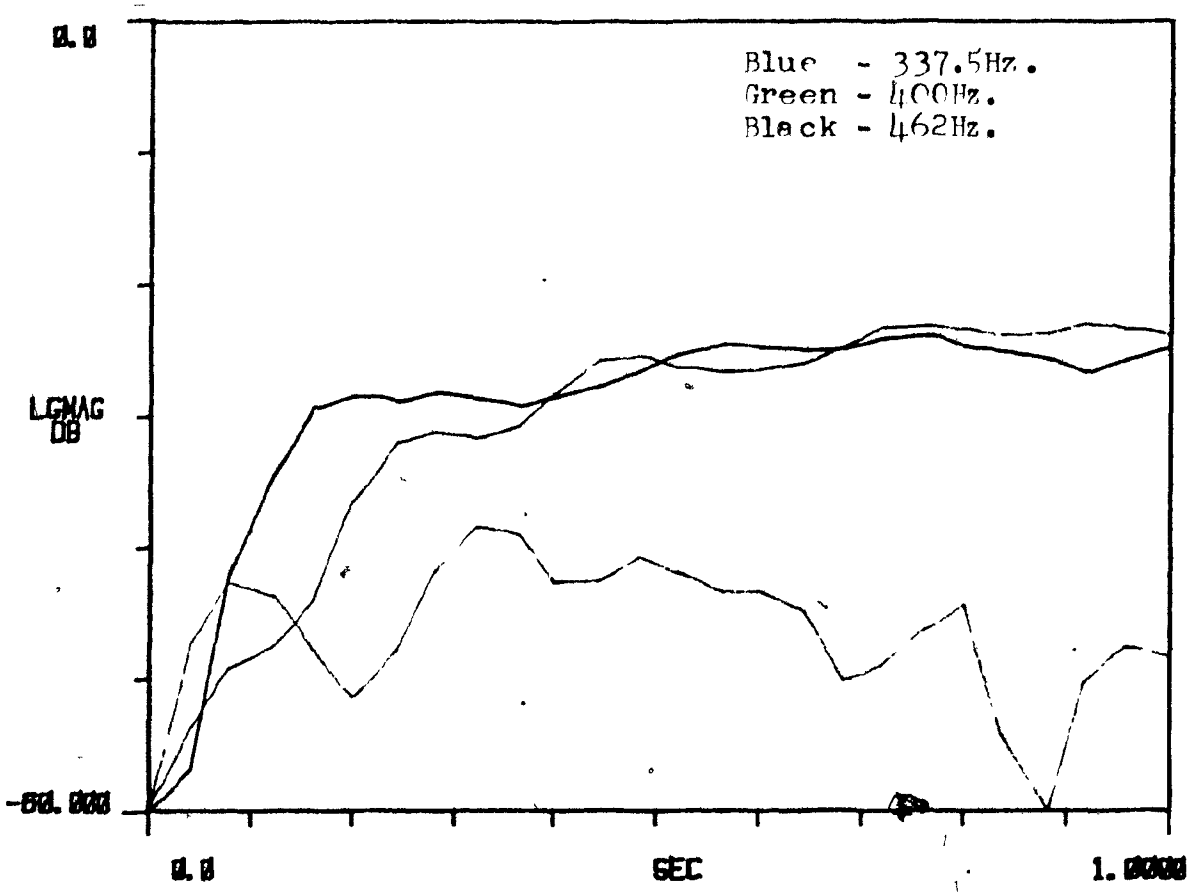

0.0
LGMAG
DB
-60.000
Green - 337.5Hz.
Blue - 400Hz.
Red - 475.5Hz.
0.0
SEC
1.0000



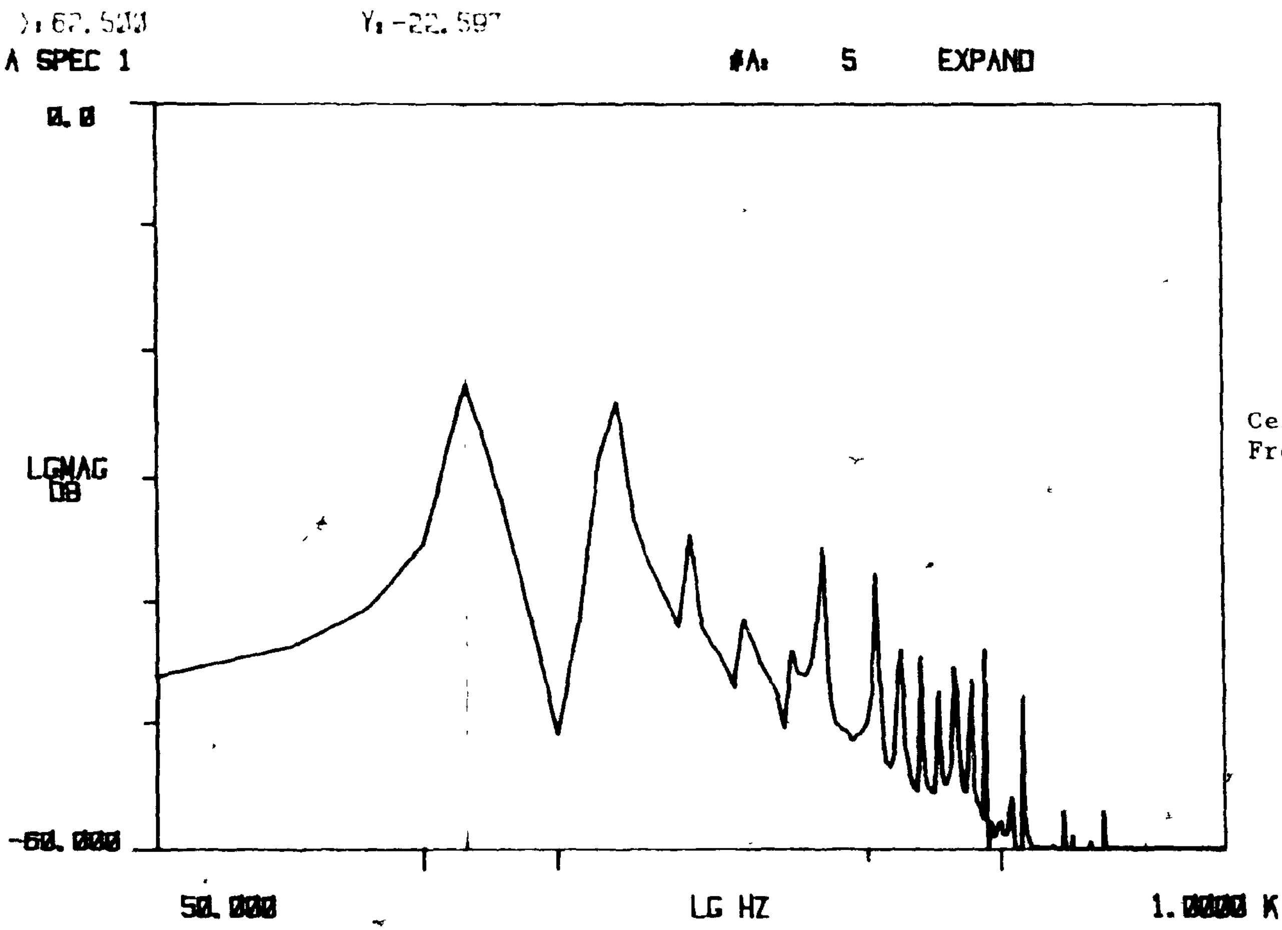
Cello Placement △2 :
Frequency Domain Analysis.



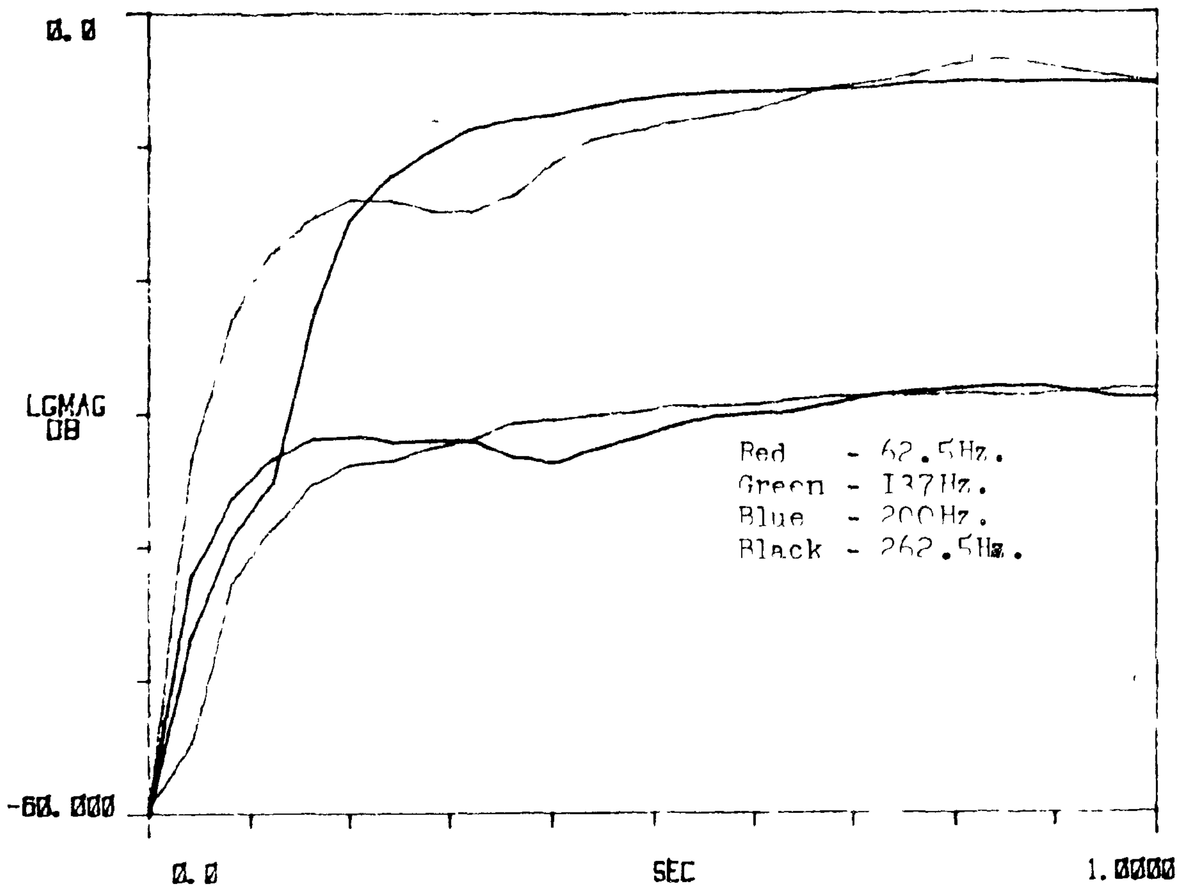
0.0
Cello Placement 2 :
Time Domain Analysis.
LGMAG DB
Green - 62.5Hz.
Black - I37Hz.
Red - 200Hz.
Blue - 262Hz.
-80.000
0.0
SEC
1.0000

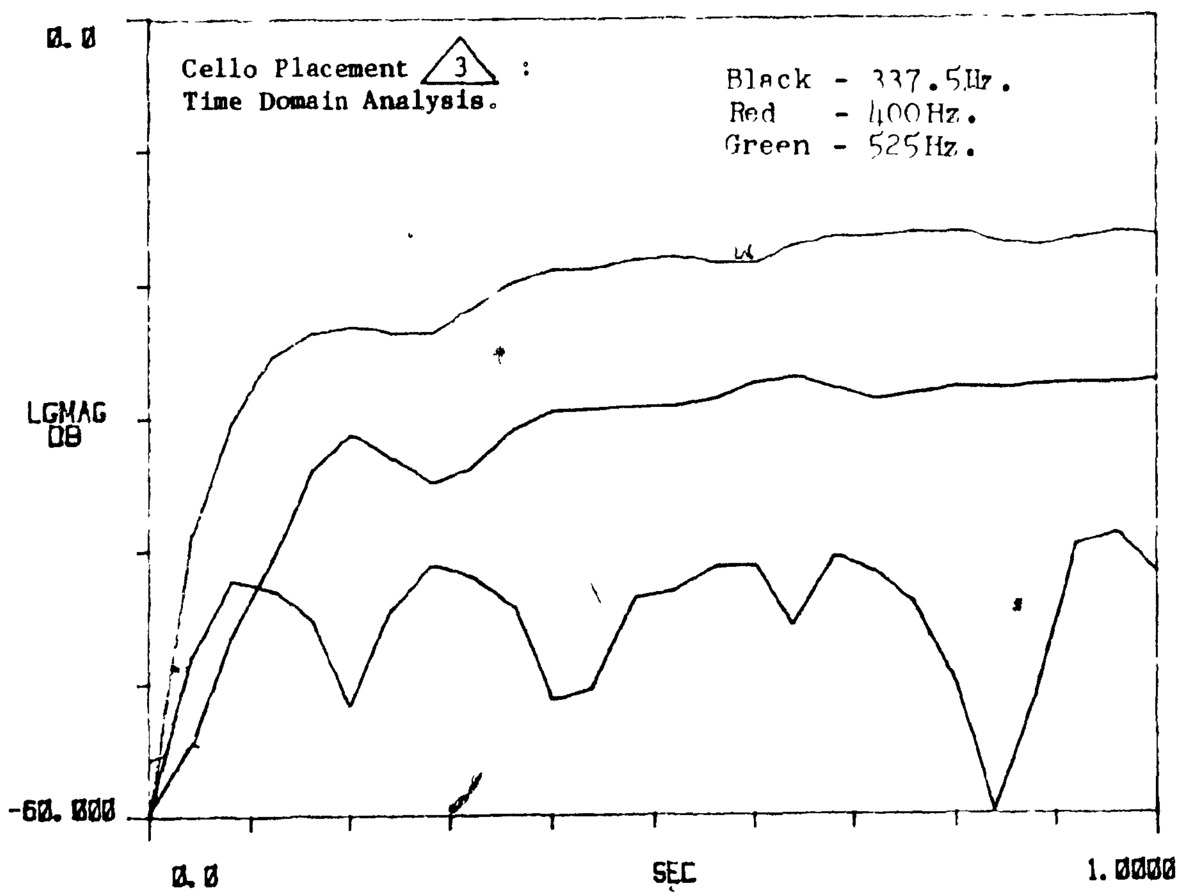


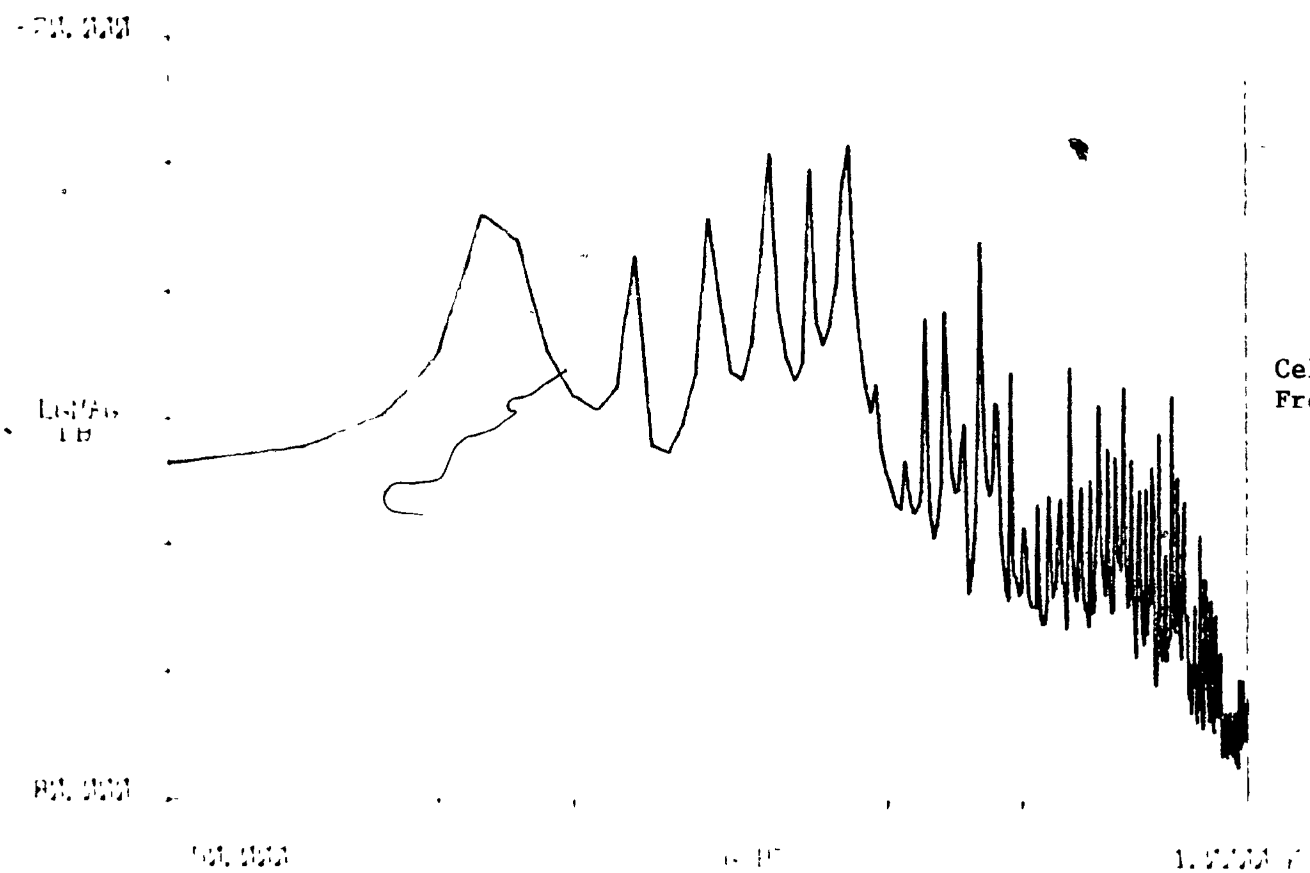
0.0
Blue - 337.5Hz.
Green - 400Hz.
Black - 462Hz.
LGMAG DB
-80.000
0.0
SEC
1.0000



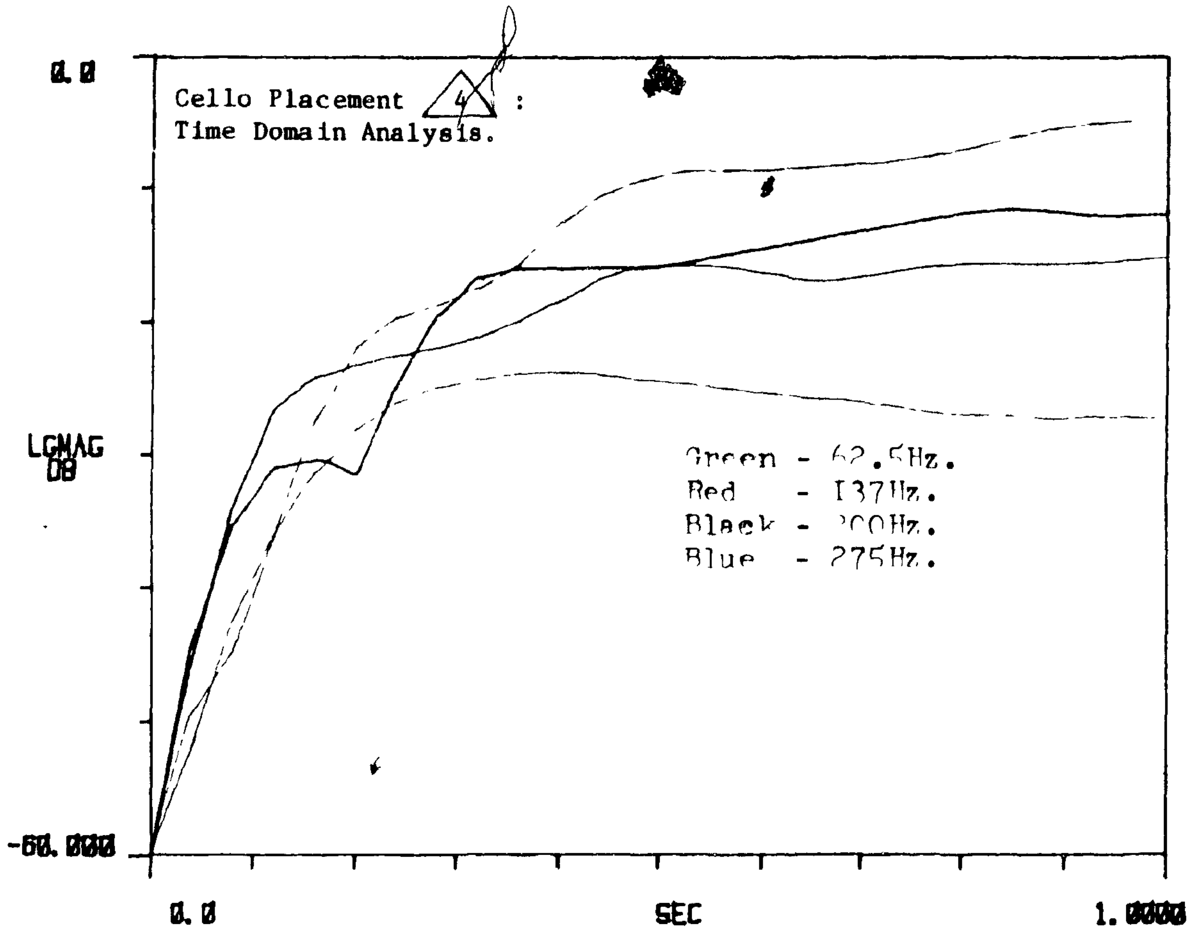
Cello Placement (3) : Frequency Domain Analysis.

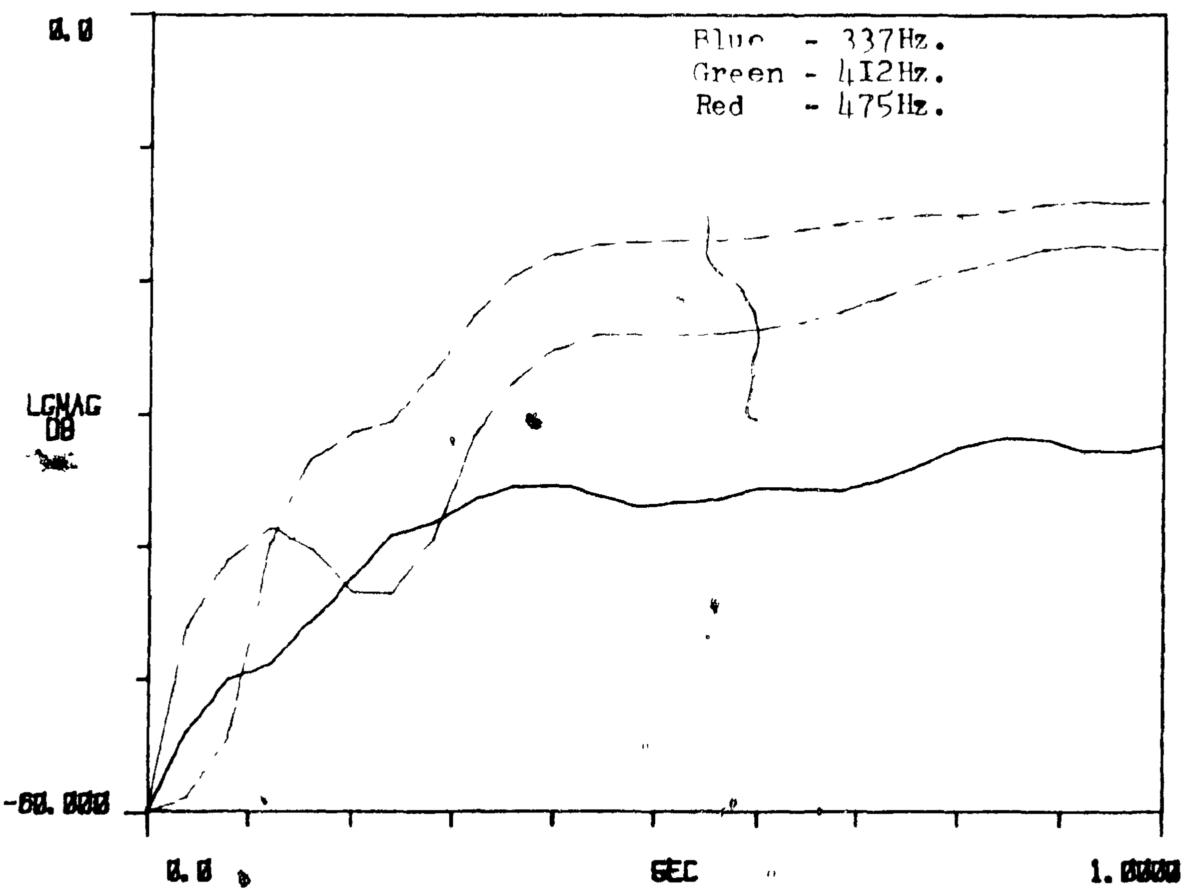

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Red - 62.5Hz.
Green - 137Hz.
Blue - 200Hz.
Black - 262.5Hz.

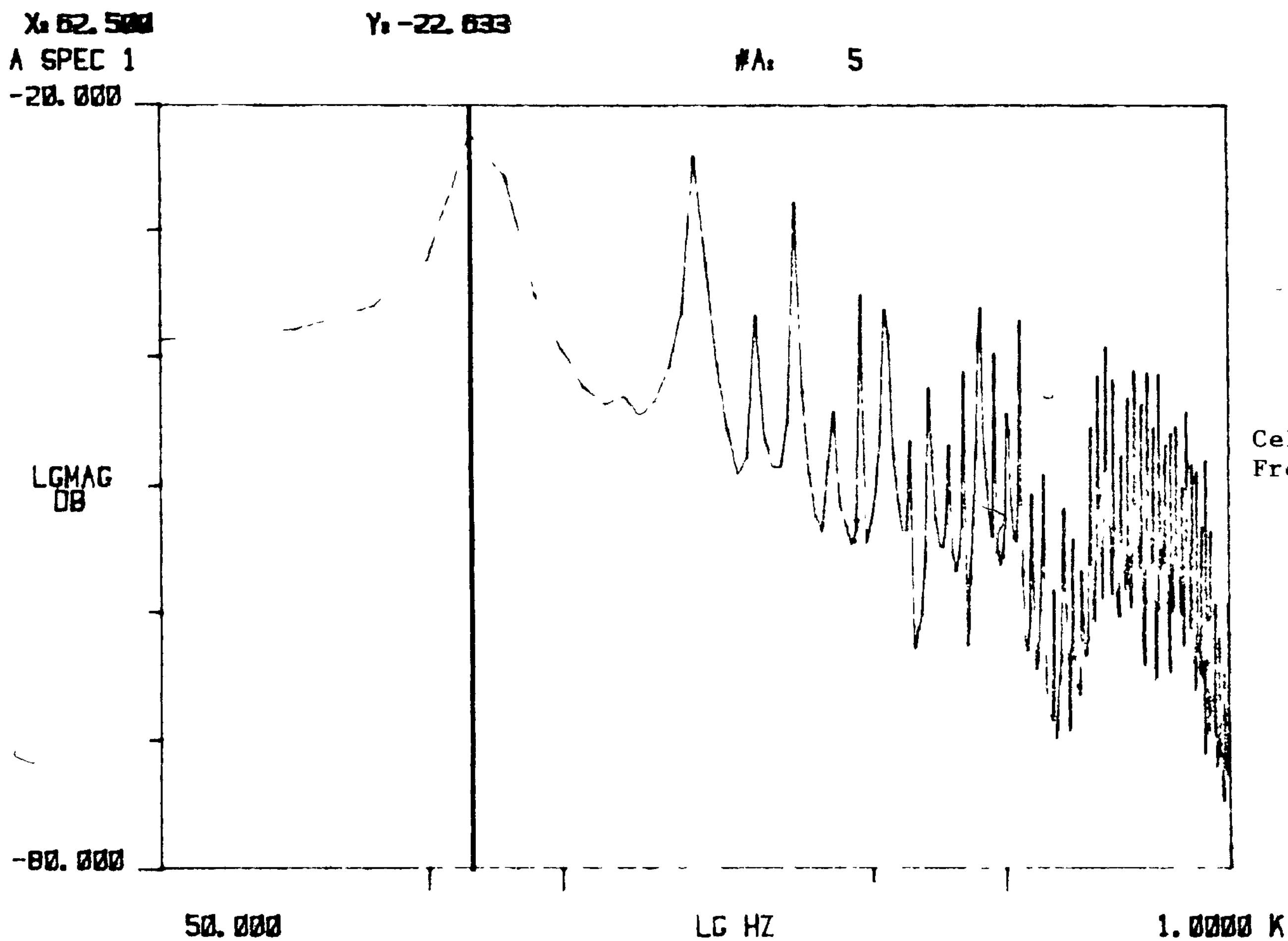

0.0
Cello Placement 3 :
Time Domain Analysis.
Black - 337.5Hz.
Red - 400Hz.
Green - 525Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000



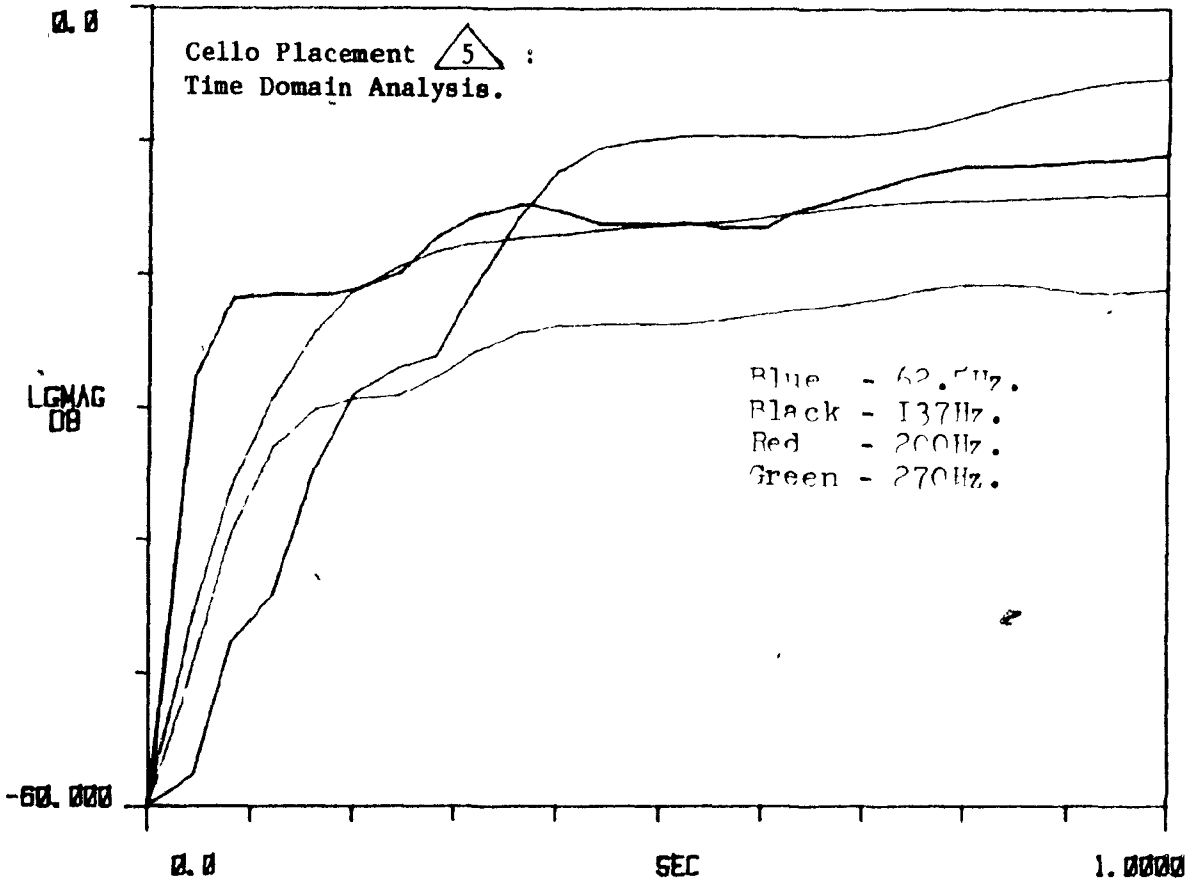
Cello Placement 4 :
Frequency Domain Analysis.

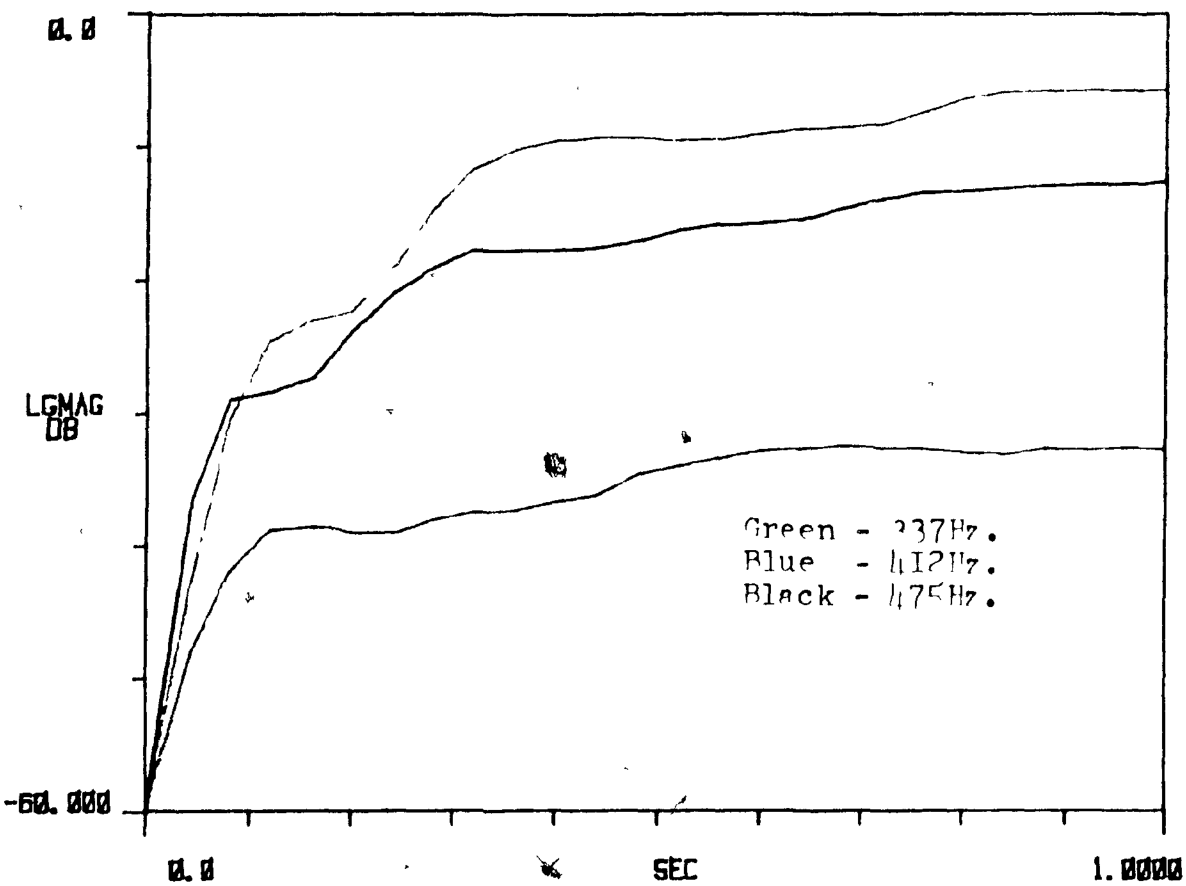

Cello Placement 4 :
Time Domain Analysis.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Green - 62.5Hz.
Red - 137Hz.
Black - 200Hz.
Blue - 275Hz.


0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Blue - 337Hz.
Green - 412Hz.
Red - 475Hz.

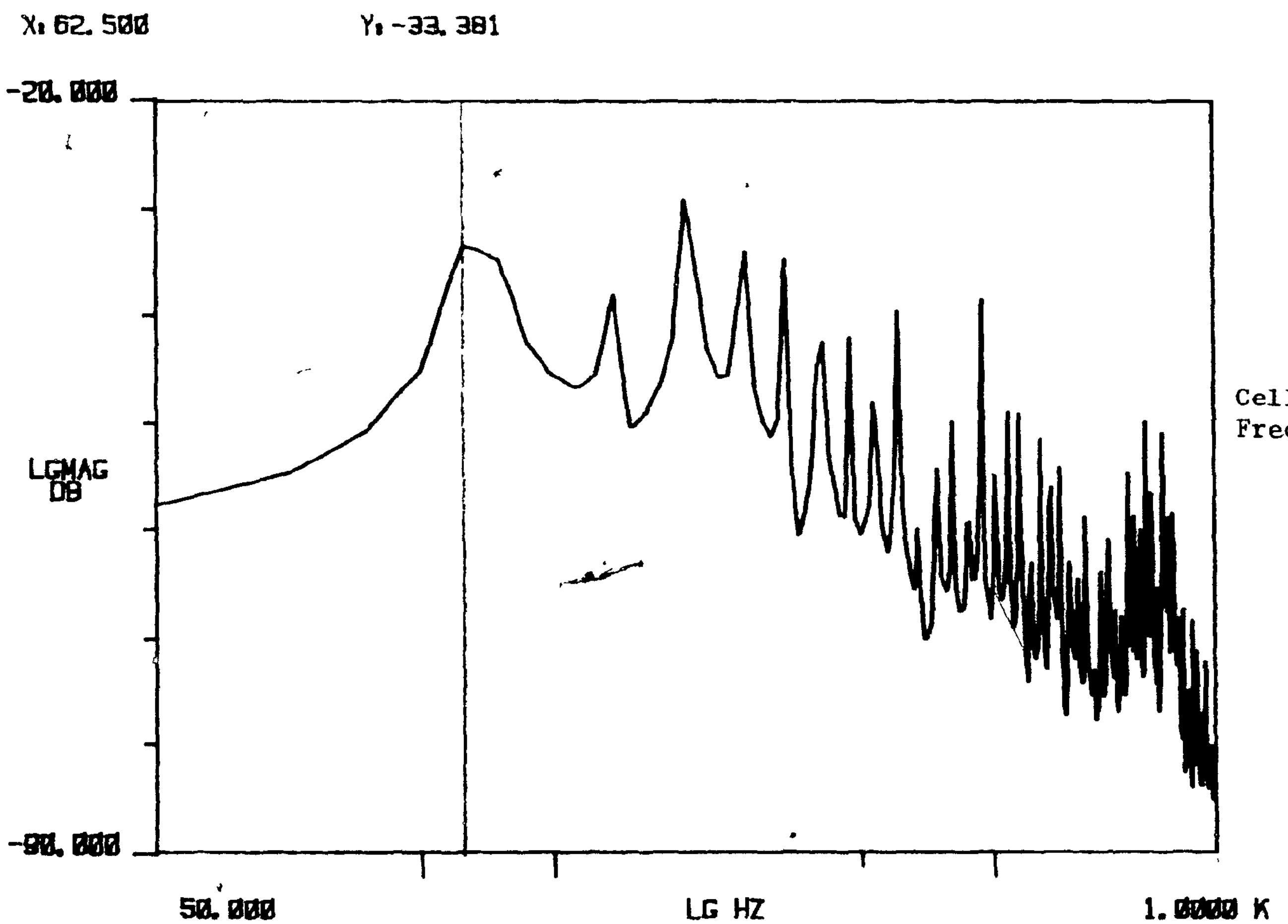


Cello Placement 5 : Frequency Domain Analysis.

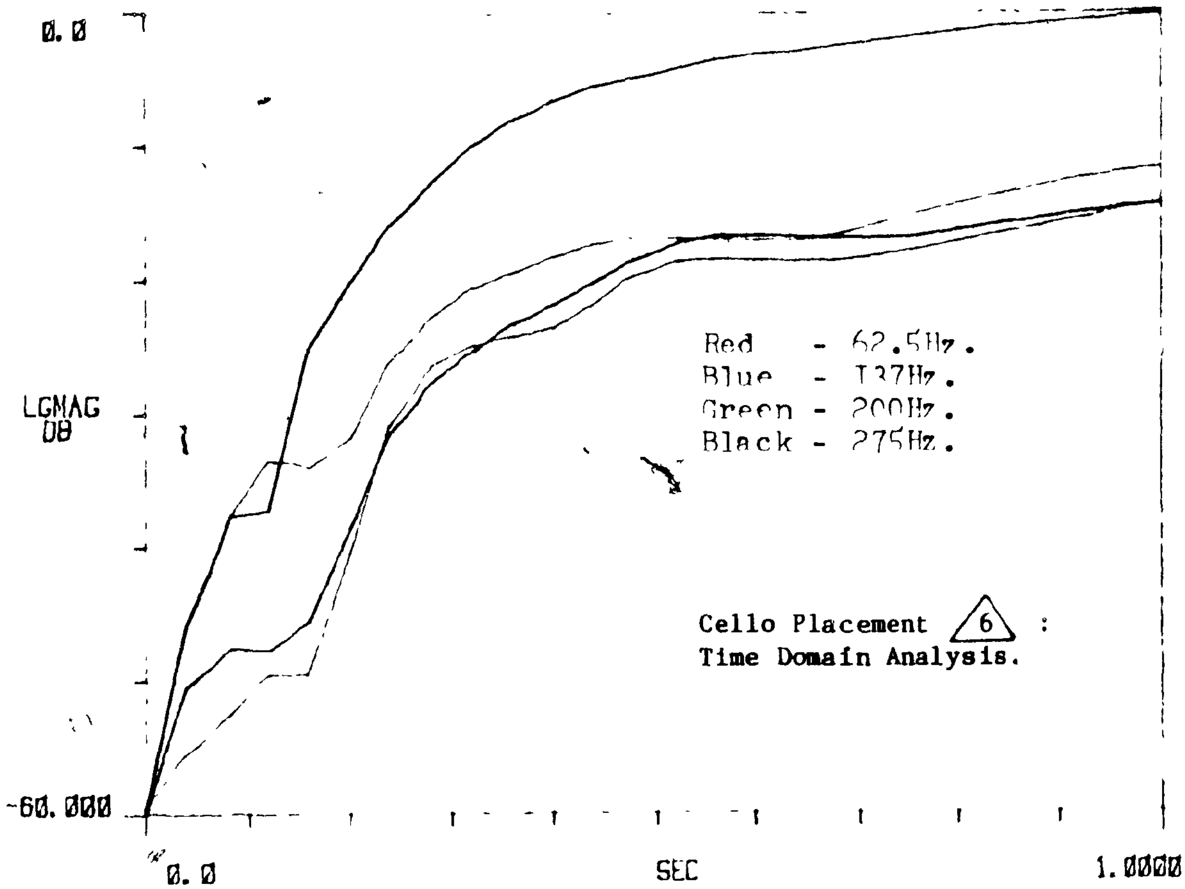

Cello Placement 5 :
Time Domain Analysis.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Blue - 62.5Hz.
Black - 137Hz.
Red - 200Hz.
Green - 270Hz.

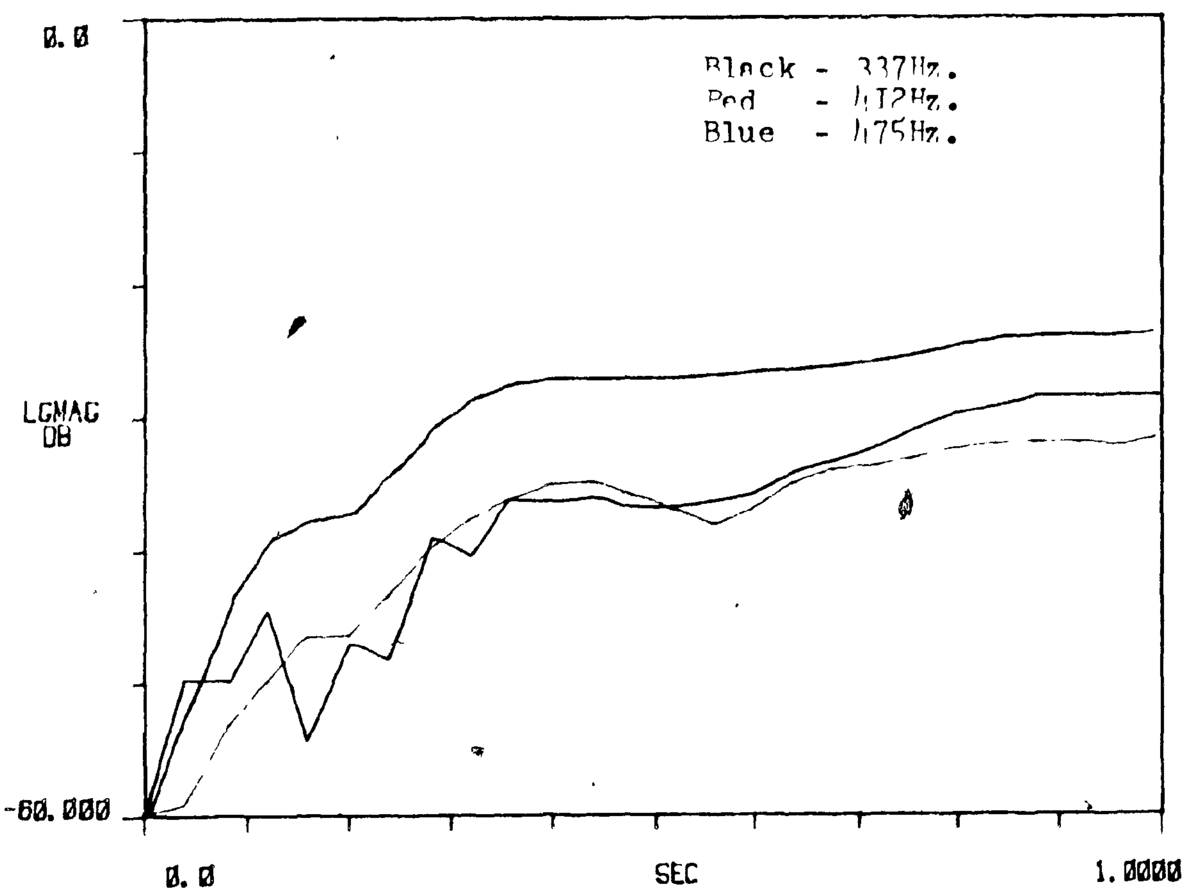

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Green - 337Hz.
Blue - 412Hz.
Black - 475Hz.

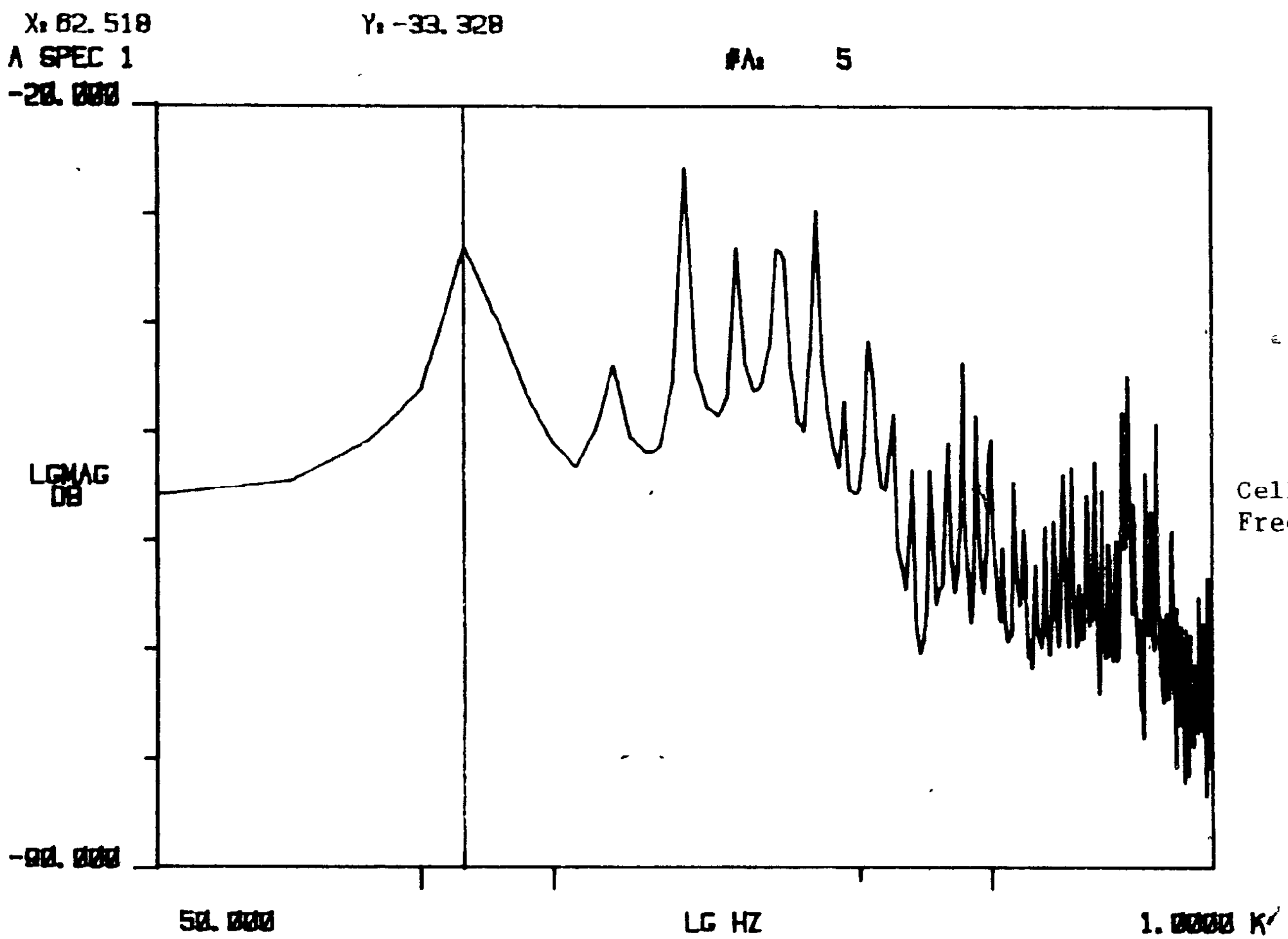
163



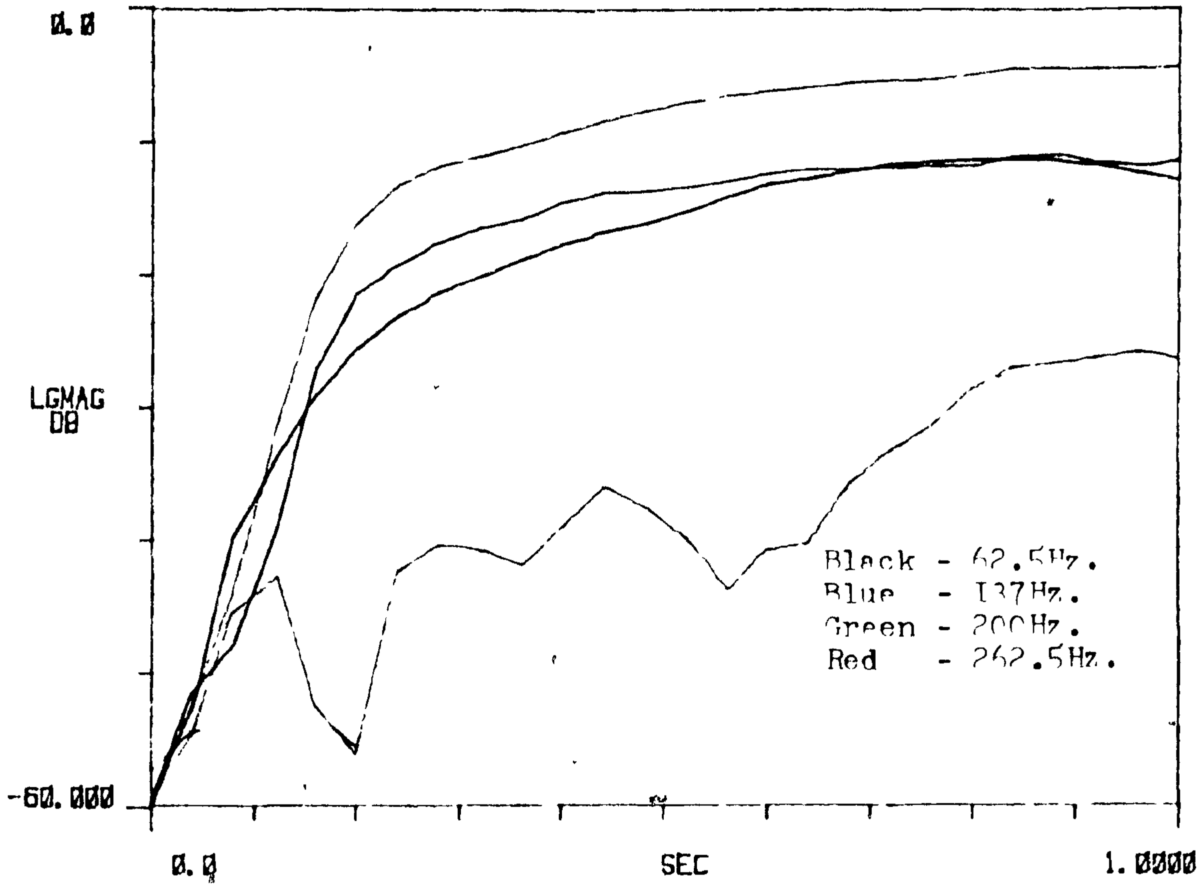
Cello Placement (6) :
Frequency Domain Analysis.

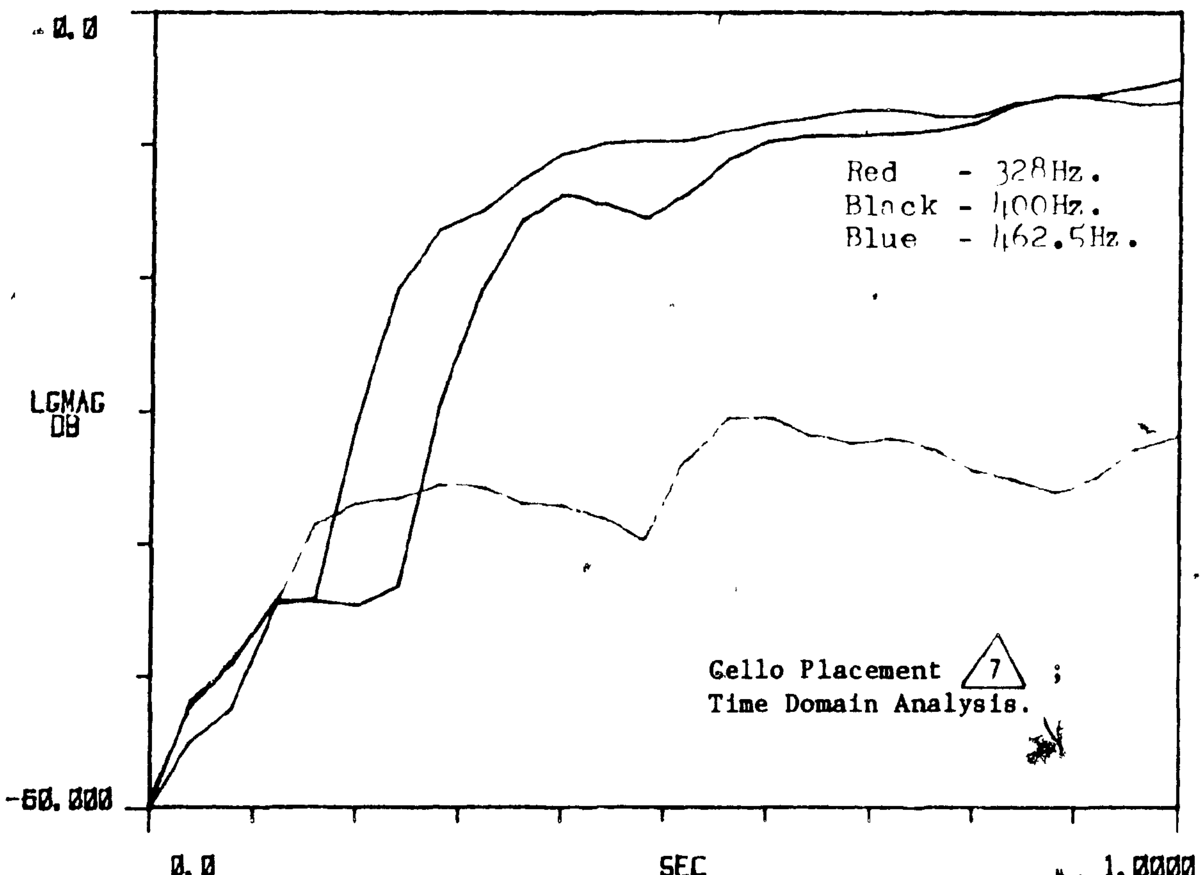

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Red - 62.5Hz.
Blue - 137Hz.
Green - 200Hz.
Black - 275Hz.
Cello Placement 6 :
Time Domain Analysis.

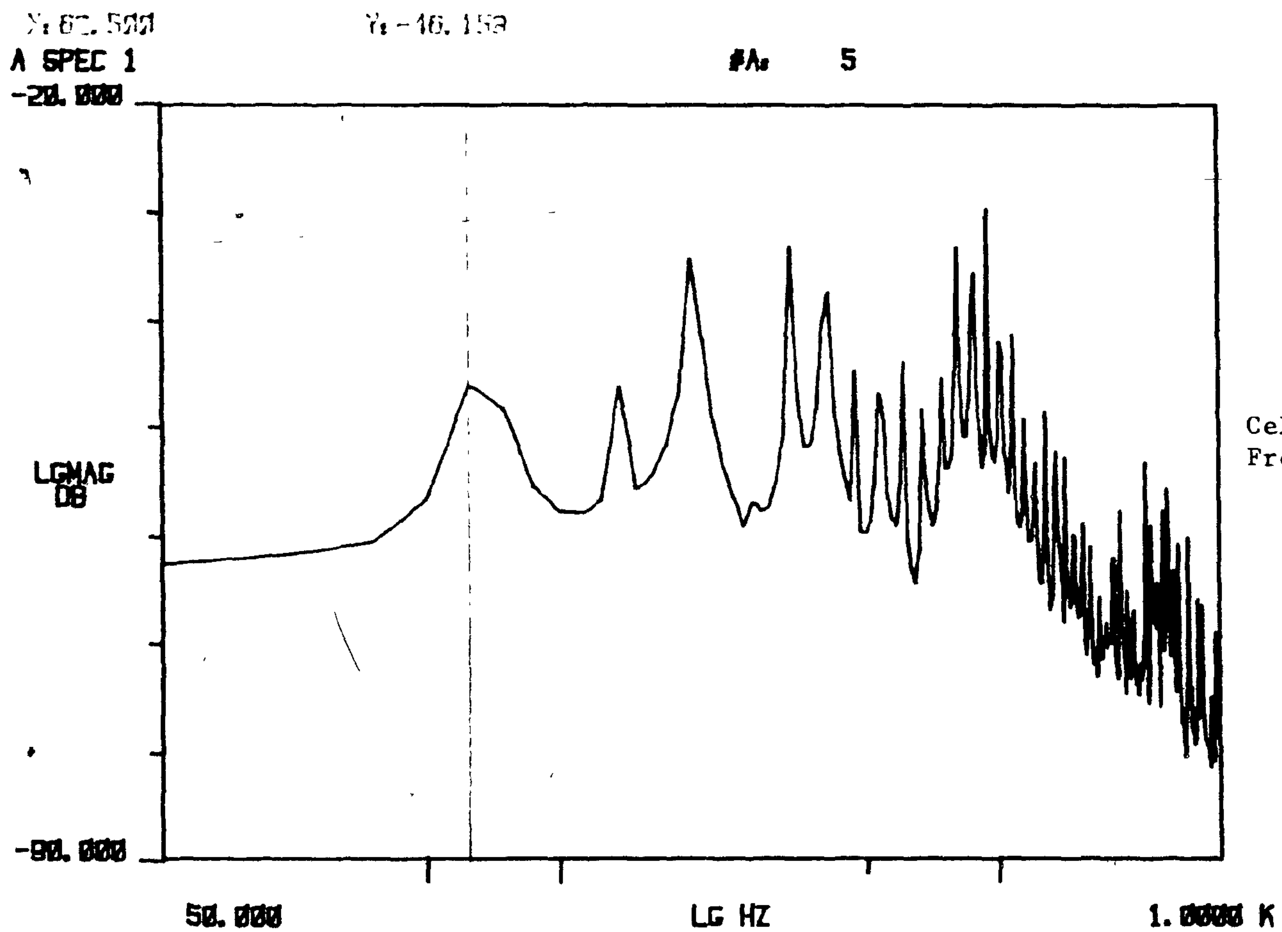

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Black - 337Hz.
Red - 412Hz.
Blue - 475Hz.



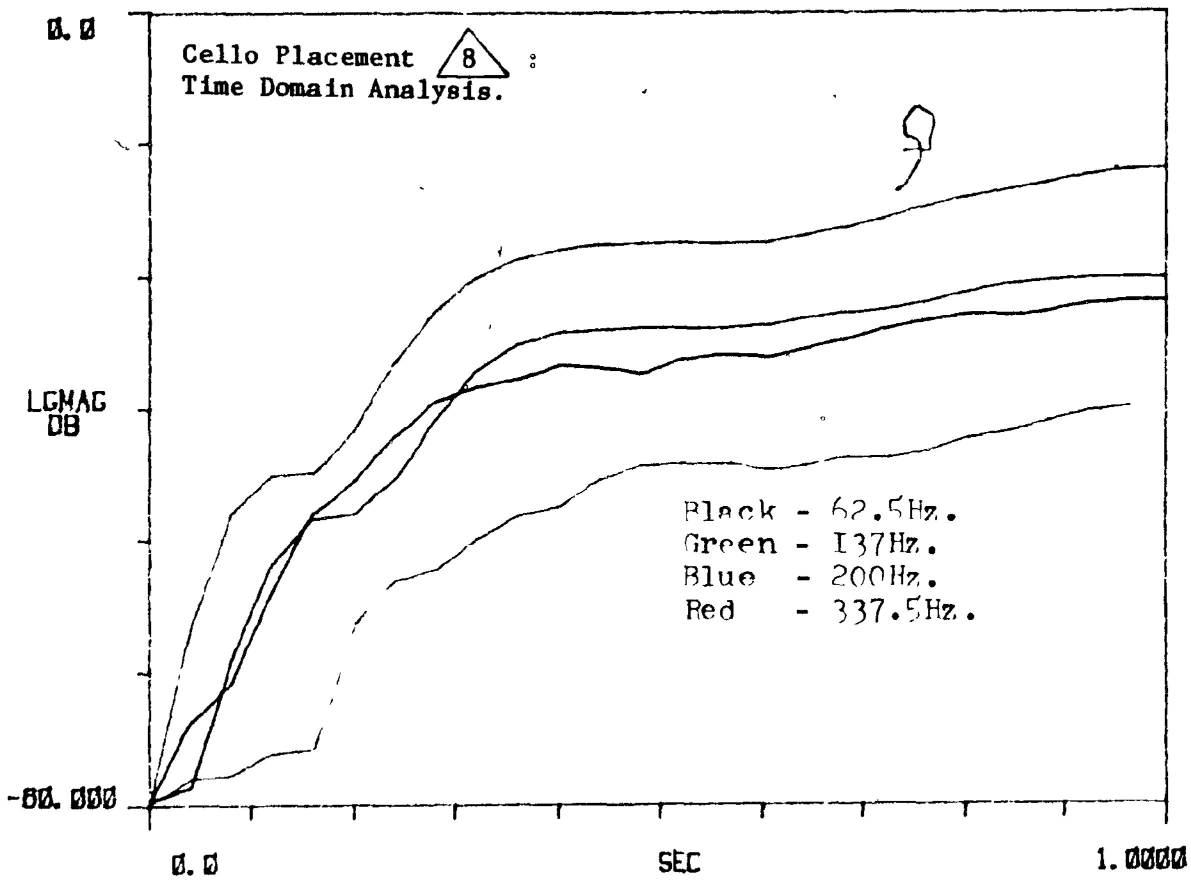
Cello Placement 7 :
Frequency Domain Analysis.


0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Black - 62.5Hz.
Blue - 137Hz.
Green - 200Hz.
Red - 262.5Hz.

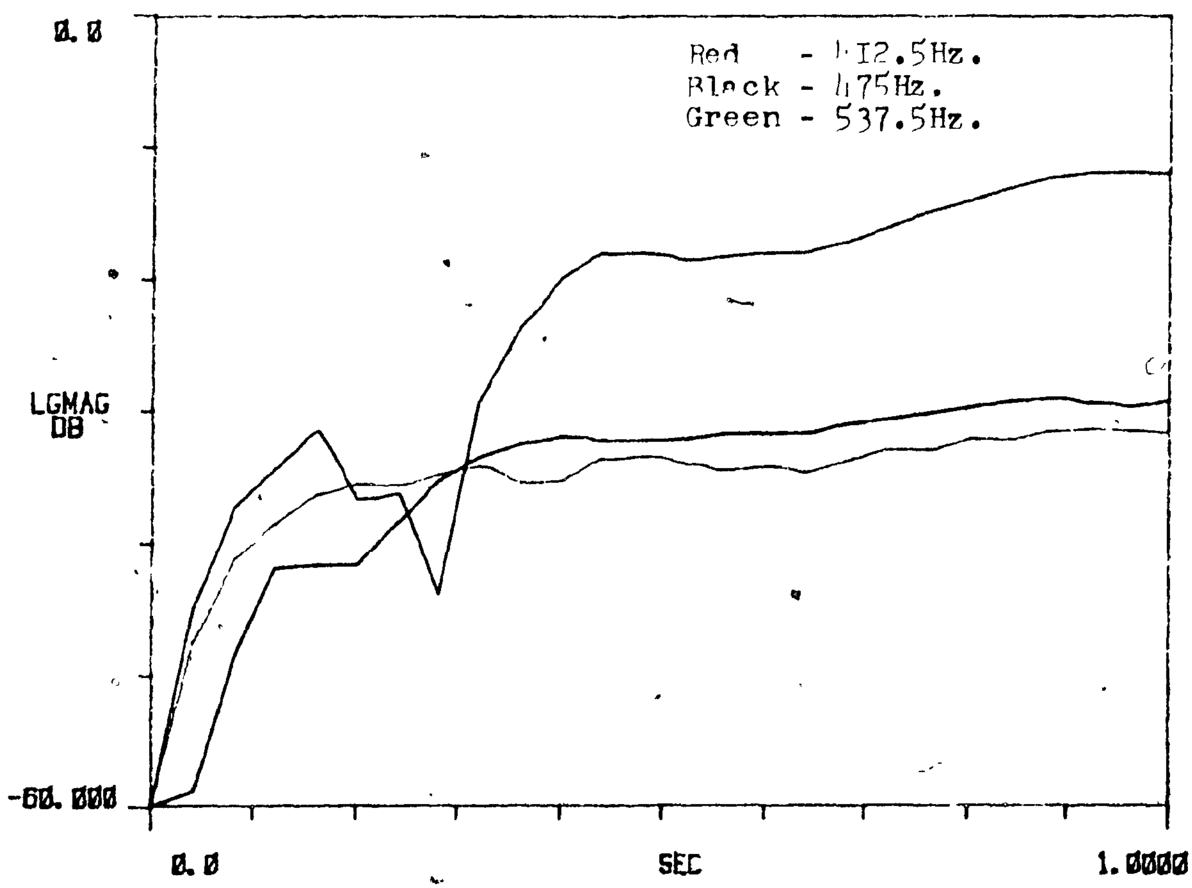

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Red - 328Hz.
Black - 400Hz.
Blue - 462.5Hz.
Cello Placement 7 ;
Time Domain Analysis.



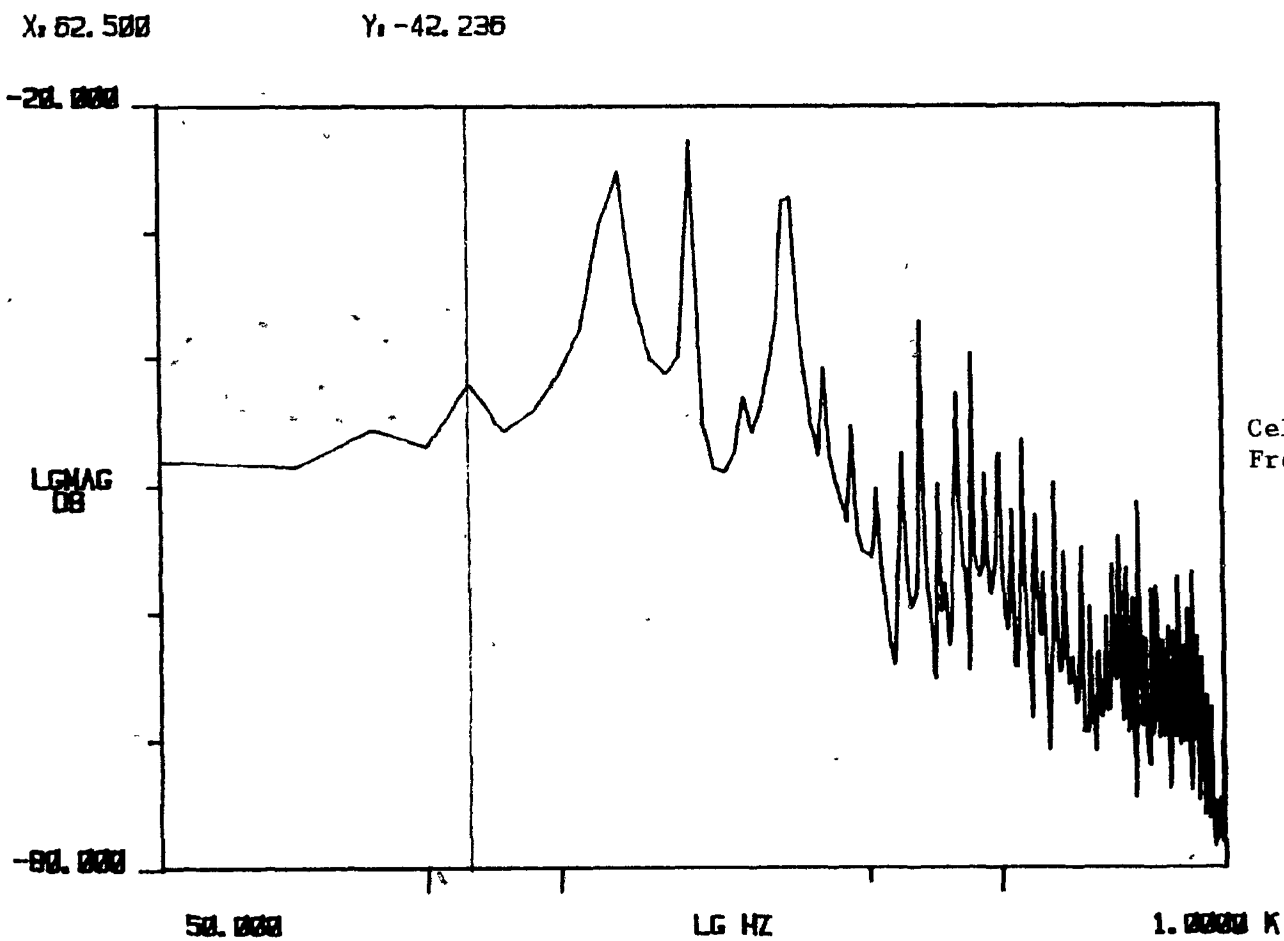
Cello Placement (8) :
Frequency Domain Analysis.



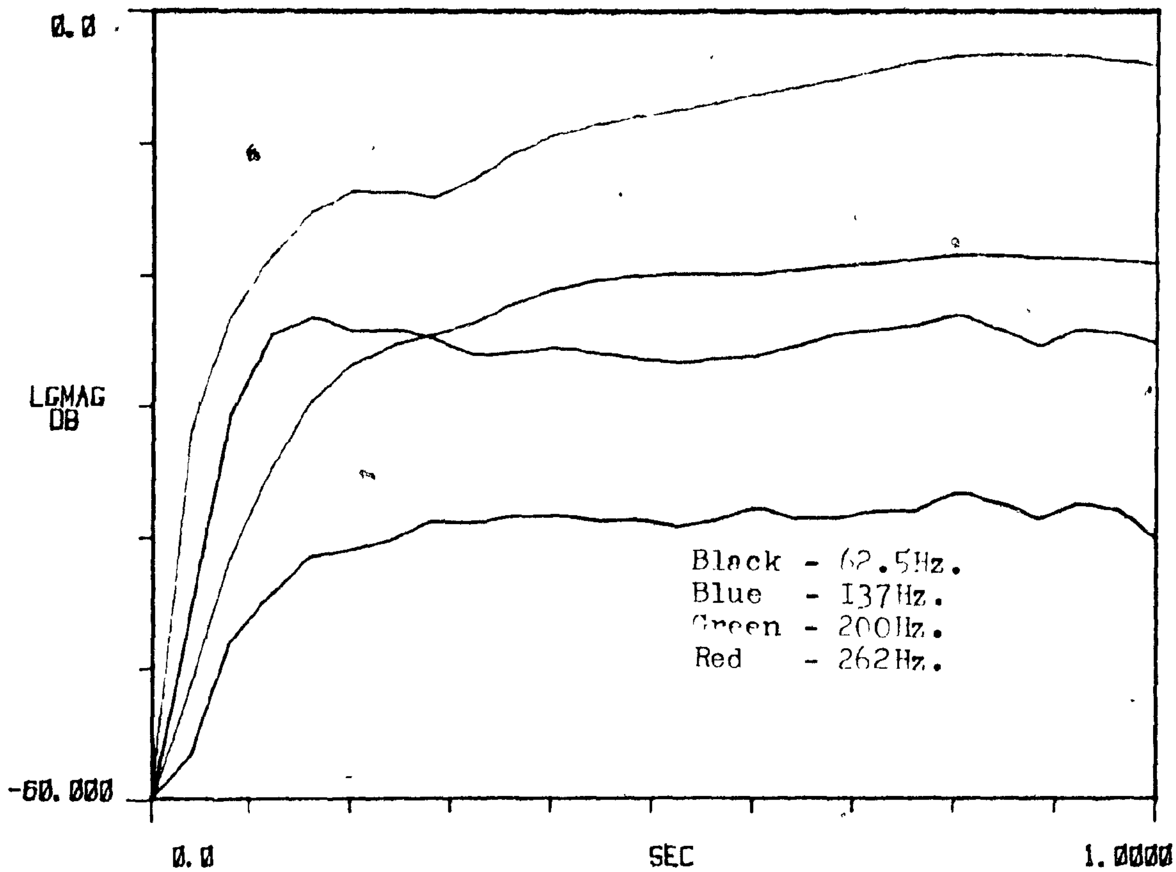
Cello Placement 8 :
Time Domain Analysis.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Black - 62.5Hz.
Green - 137Hz.
Blue - 200Hz.
Red - 337.5Hz.

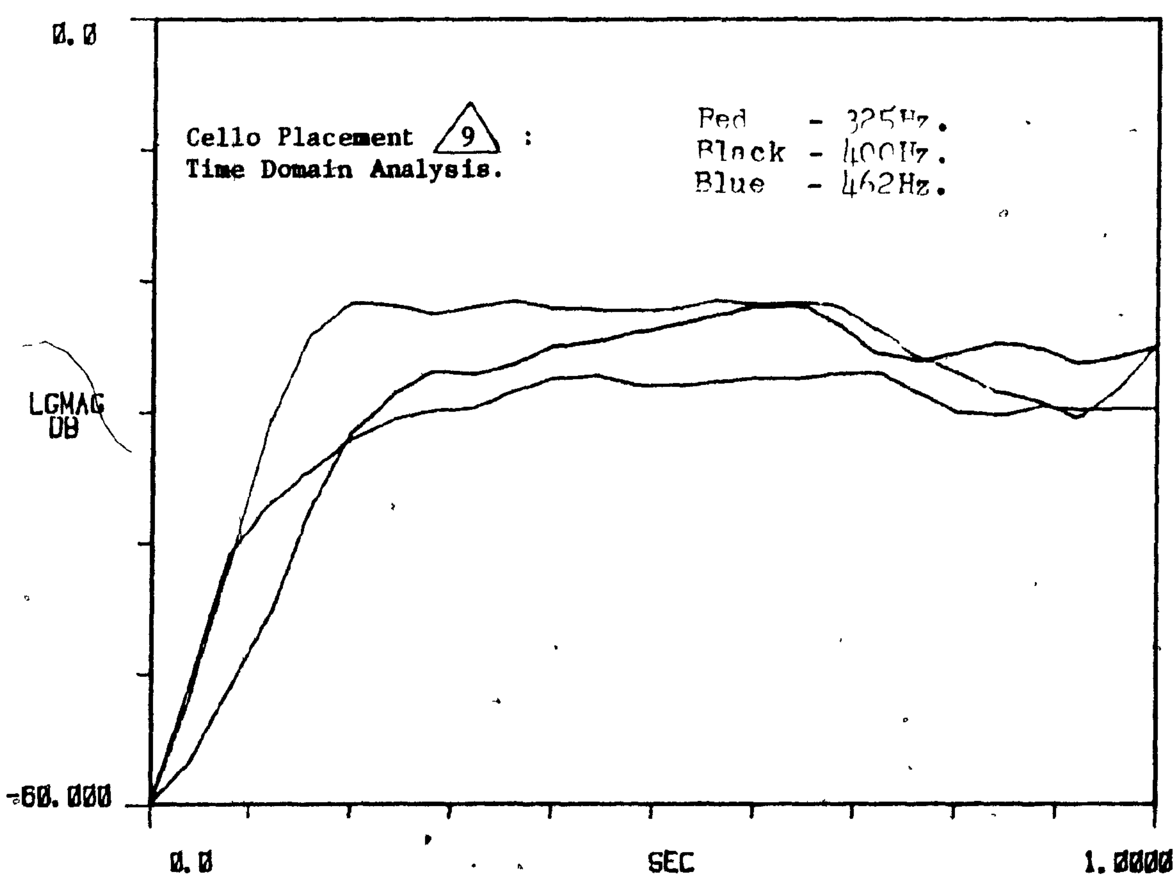


0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Red - 412.5Hz.
Black - 475Hz.
Green - 537.5Hz.



Cello Placement 9 :
Frequency Domain Analysis.

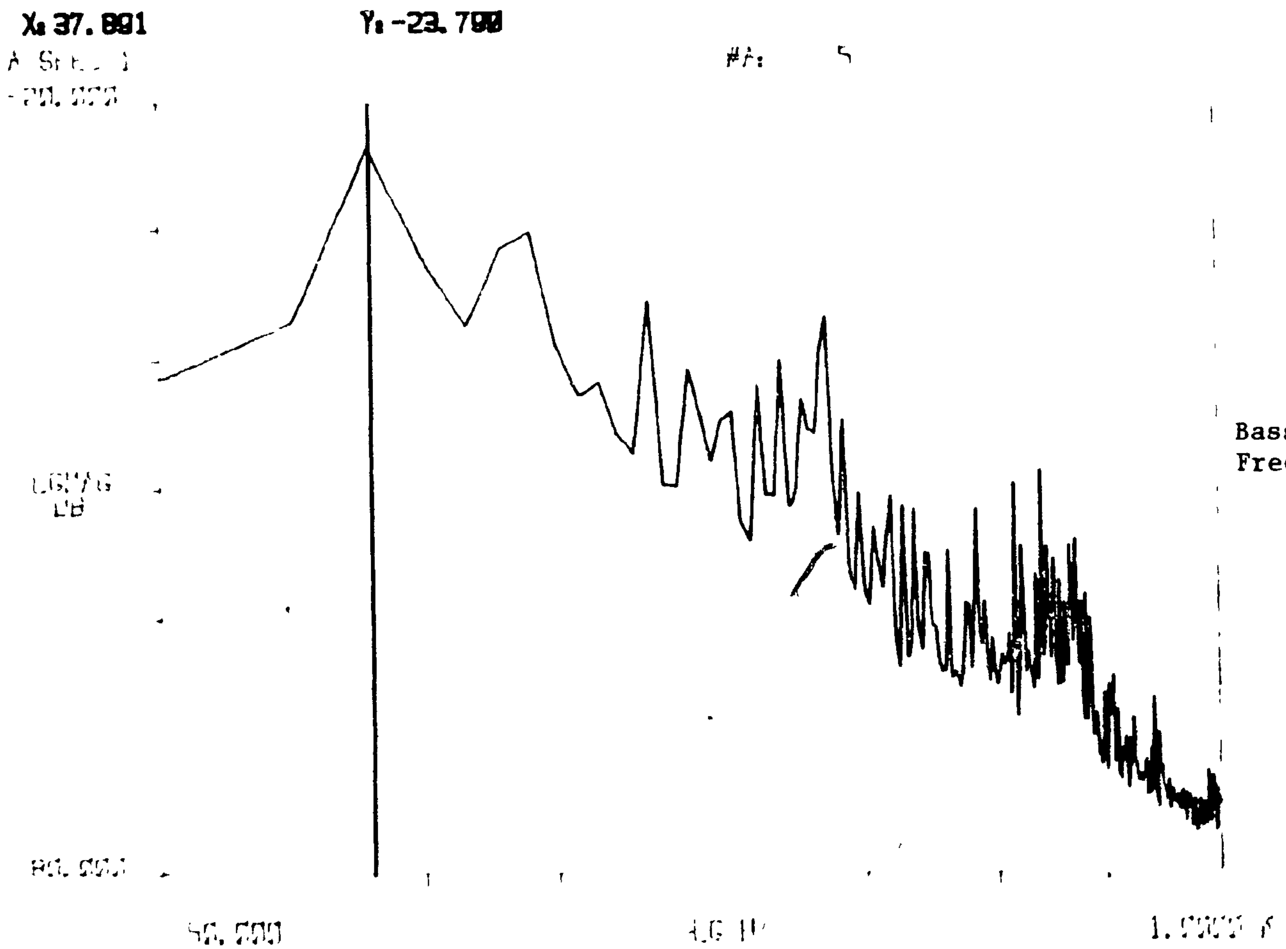

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Black - 62.5Hz.
Blue - 137Hz.
Green - 200Hz.
Red - 262Hz.


0.0
Cello Placement 9 :
Time Domain Analysis.
Red - 325Hz.
Black - 400Hz.
Blue - 462Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

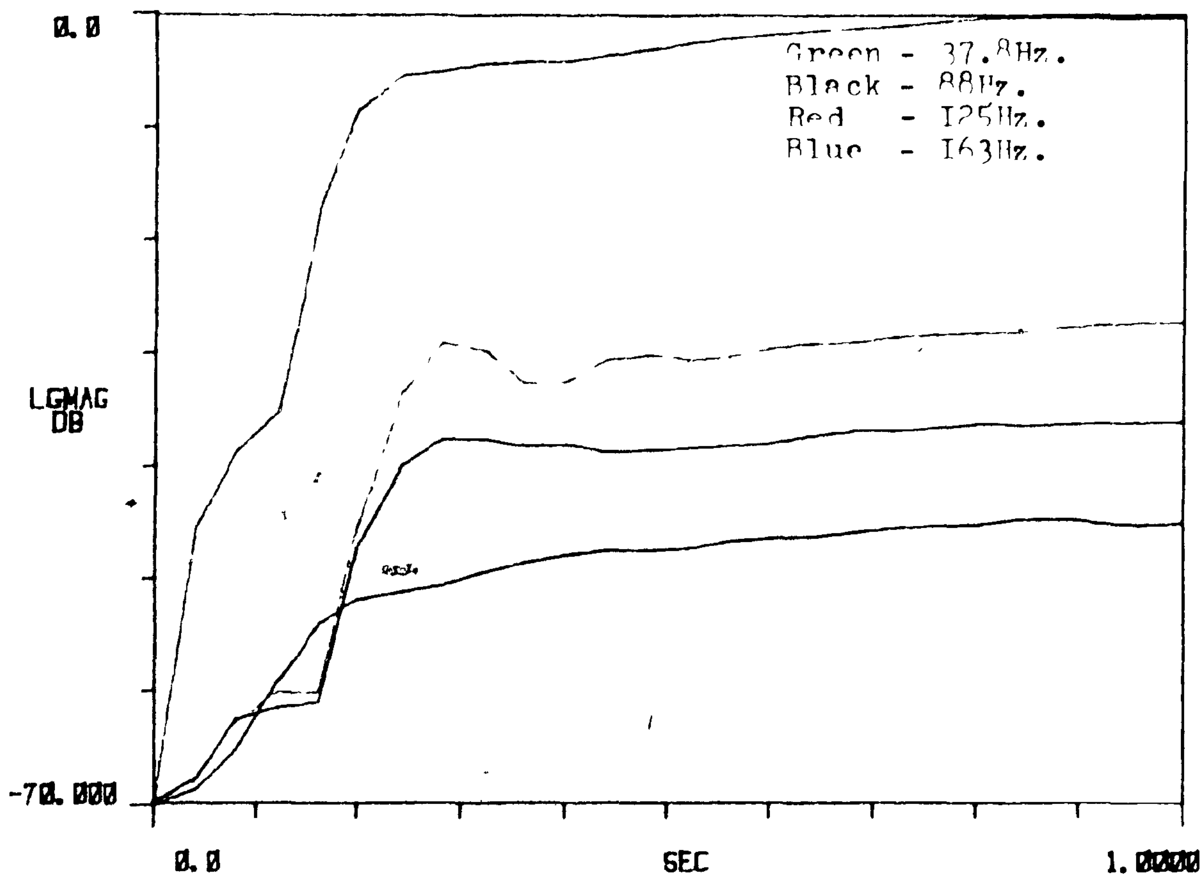
APPENDIX IV

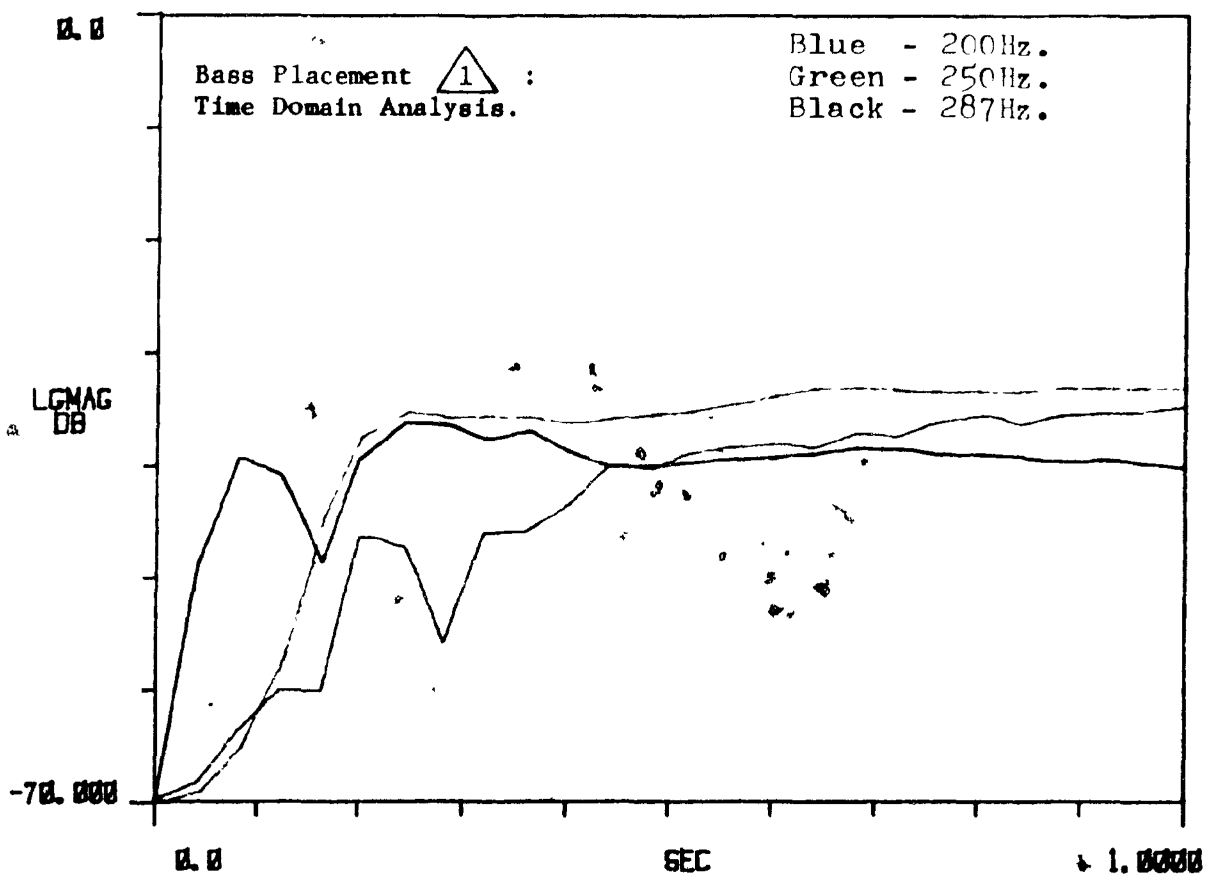
Bass

Spectrum Analysis

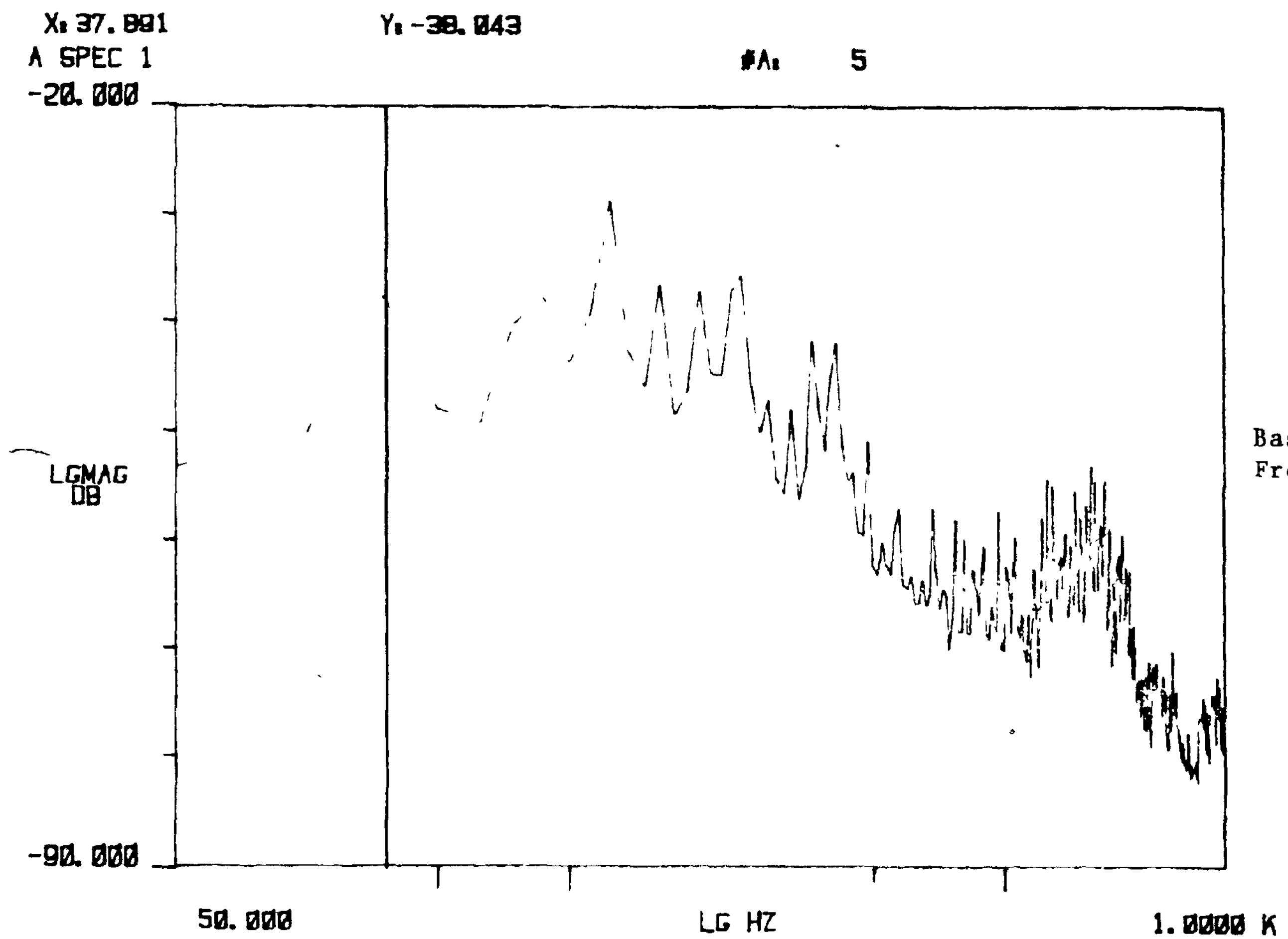


Bass Placement △1 :
Frequency Domain Analysis.

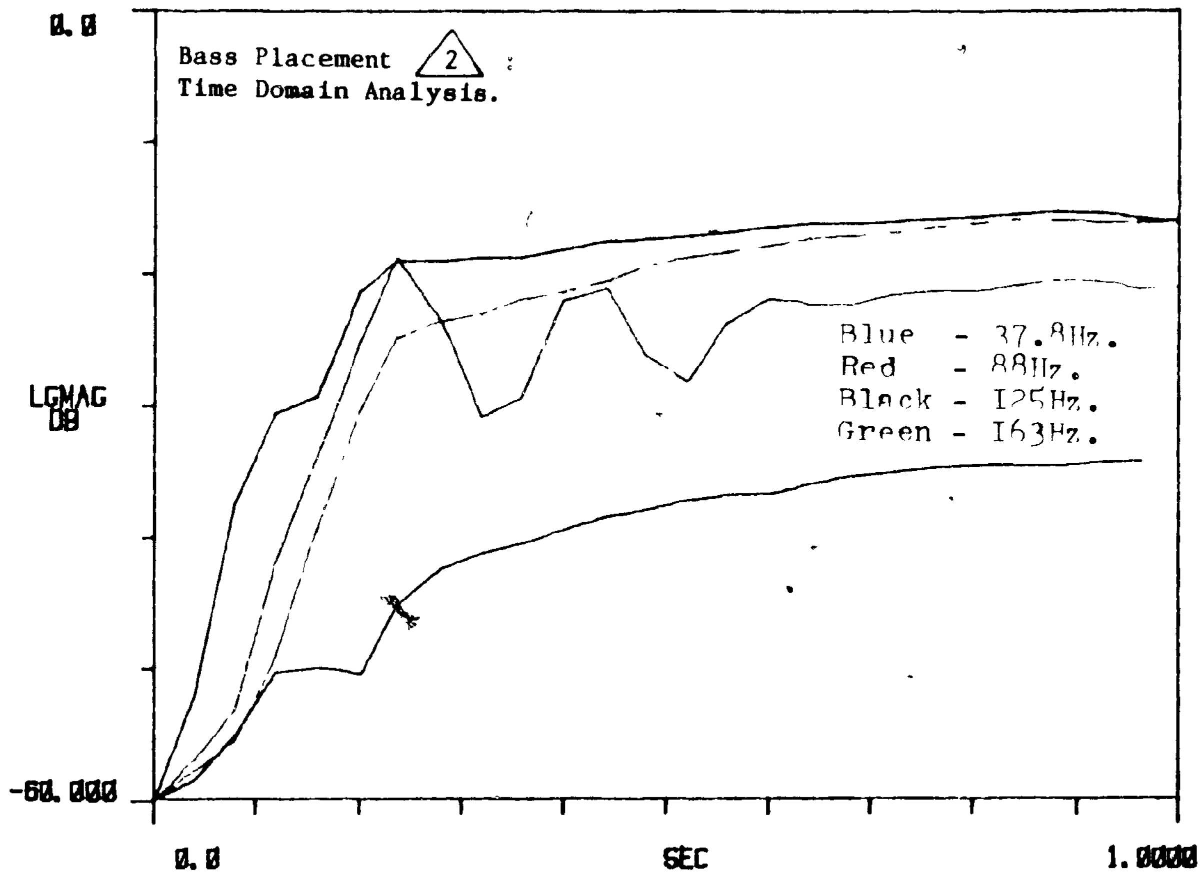


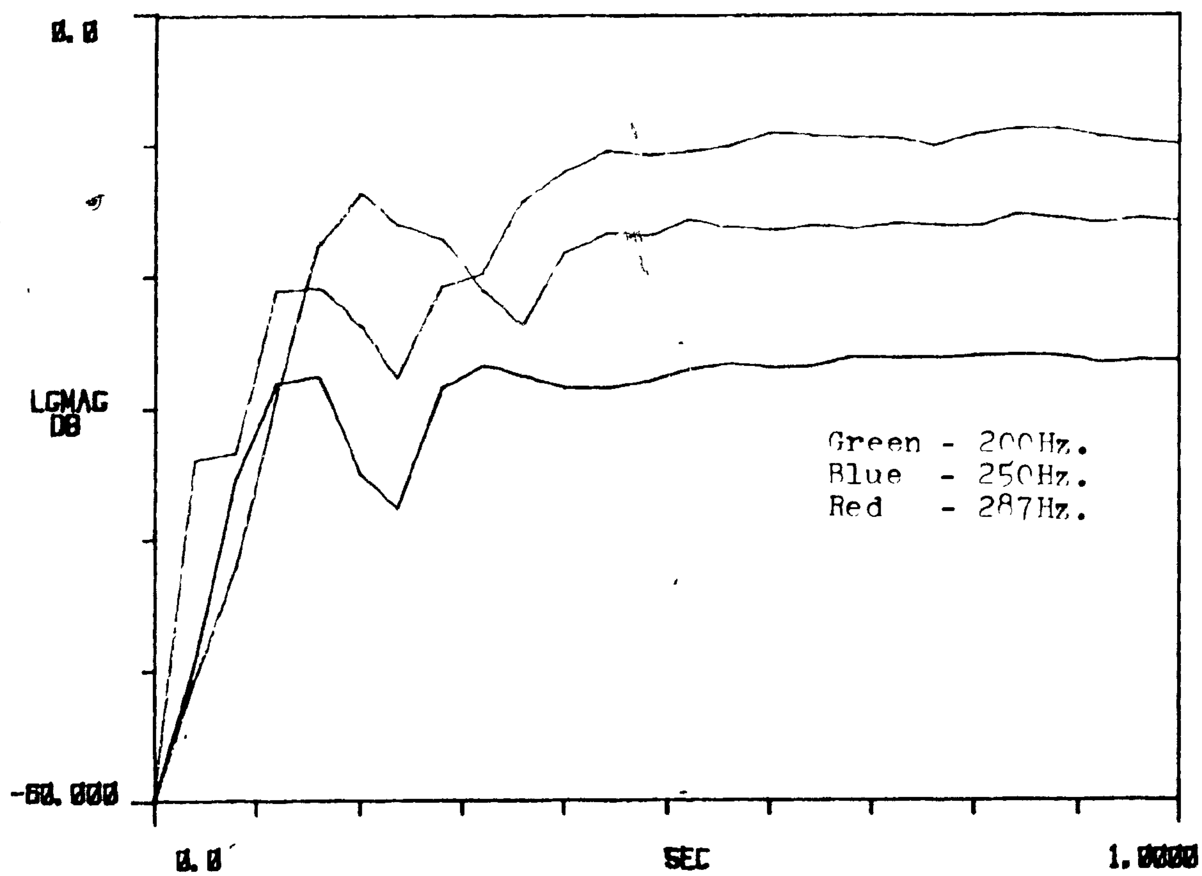


Bass Placement 1 :
Time Domain Analysis.

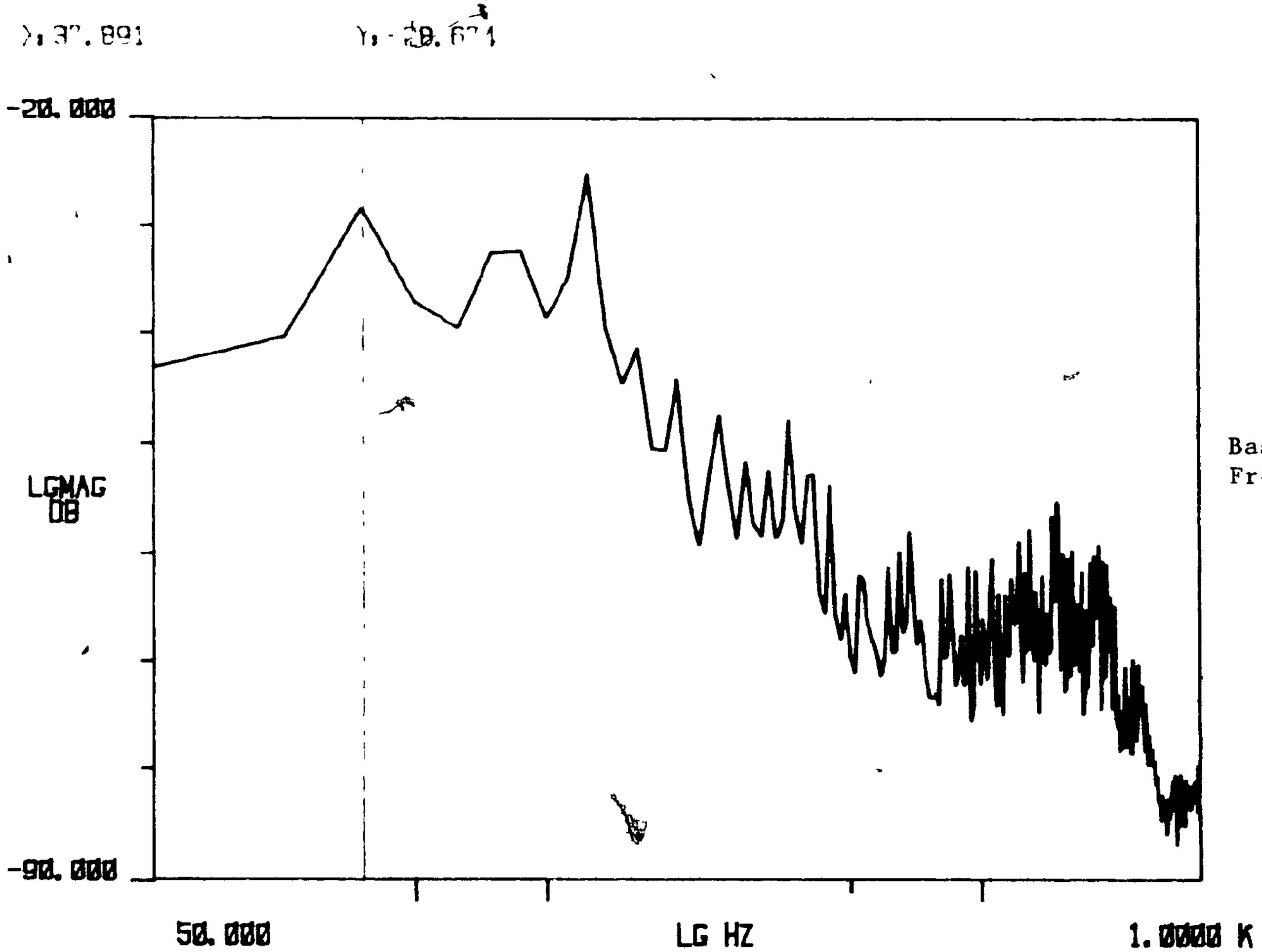


Bass Placement (2) :
Frequency Domain Analysis.

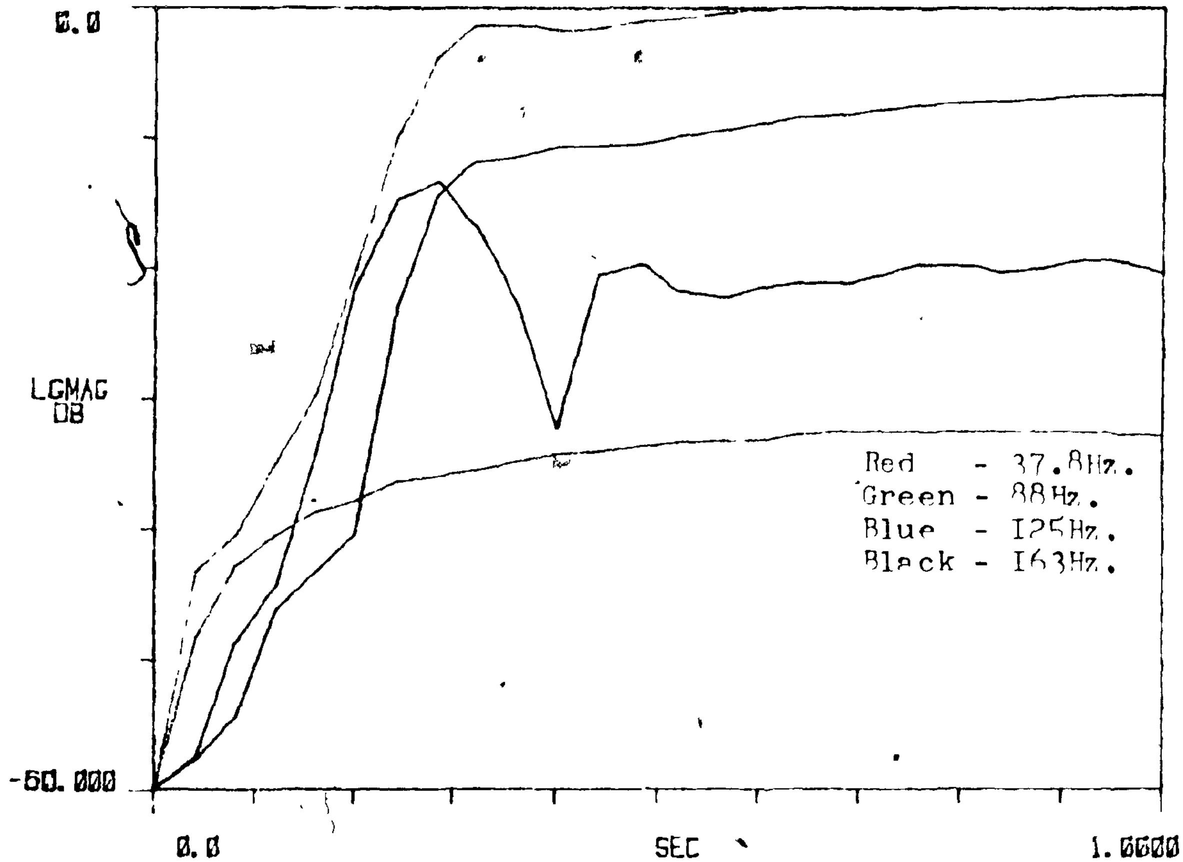

0.0
Bass Placement 2
Time Domain Analysis.
Blue - 37.8Hz.
Red - 88Hz.
Black - I25Hz.
Green - I63Hz.
LGMAG DB
-60.000
0.0
SEC
1.0000

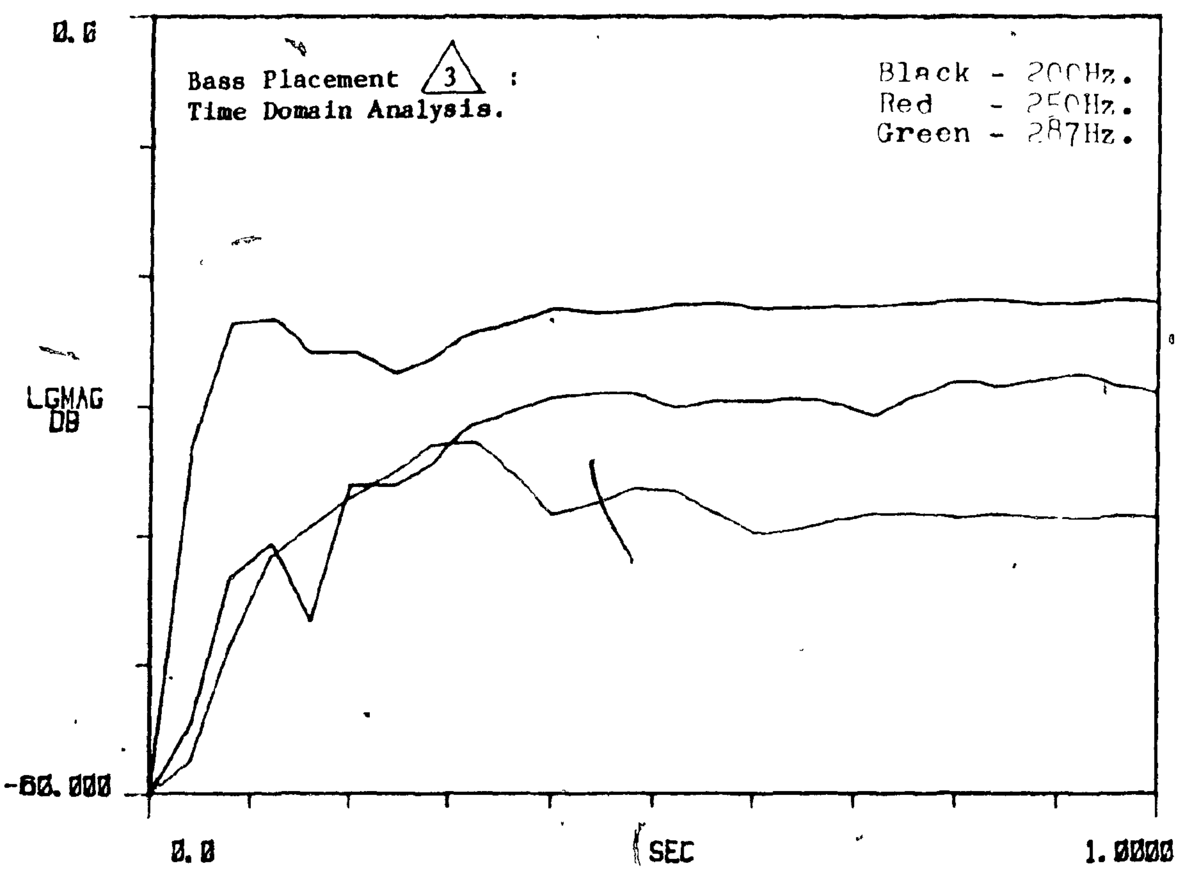

0.0
Green - 200Hz.
Blue - 250Hz.
Red - 287Hz.
LGMAG DB
-60.000
0.0
SEC
1.0000

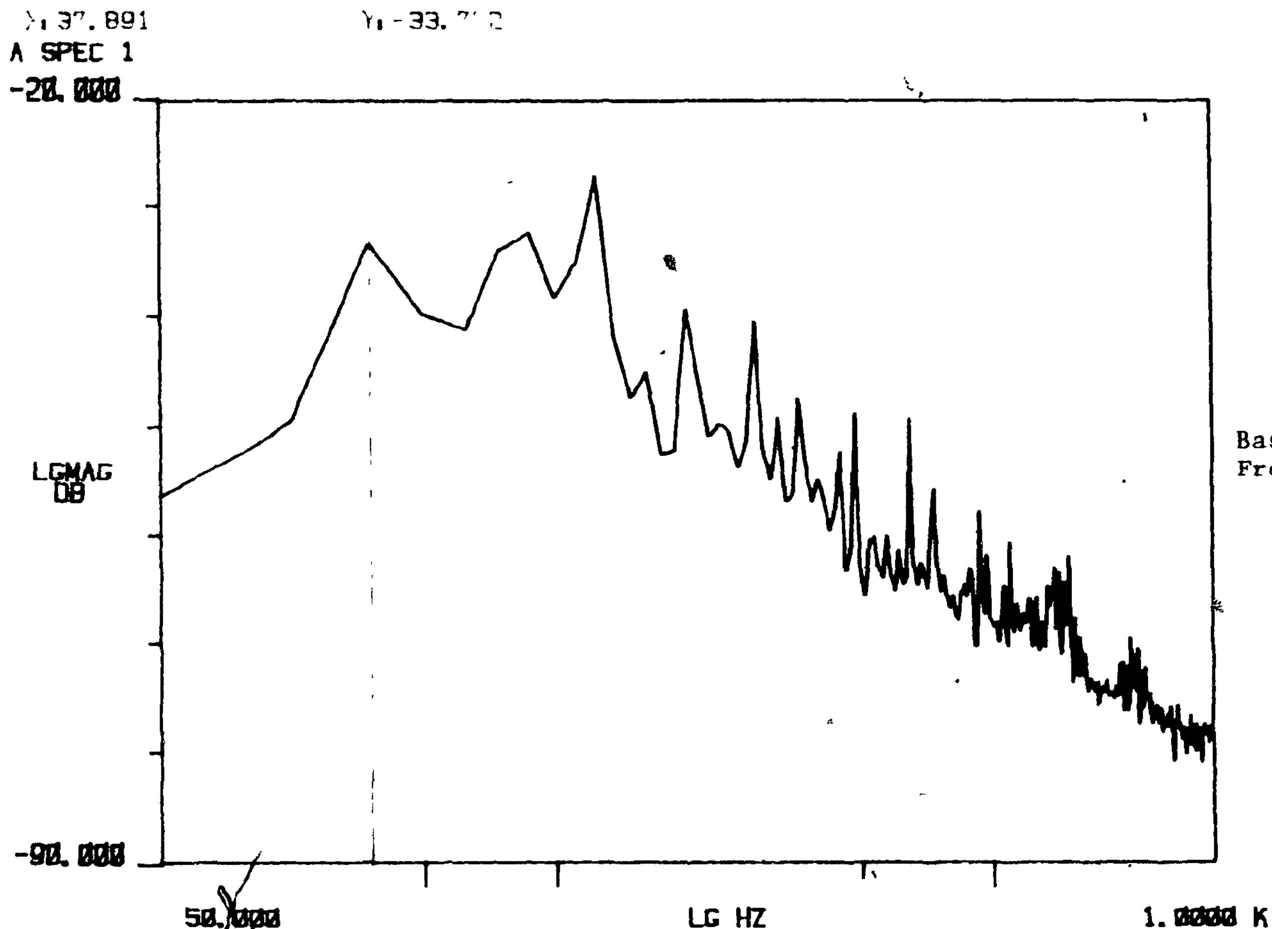
176



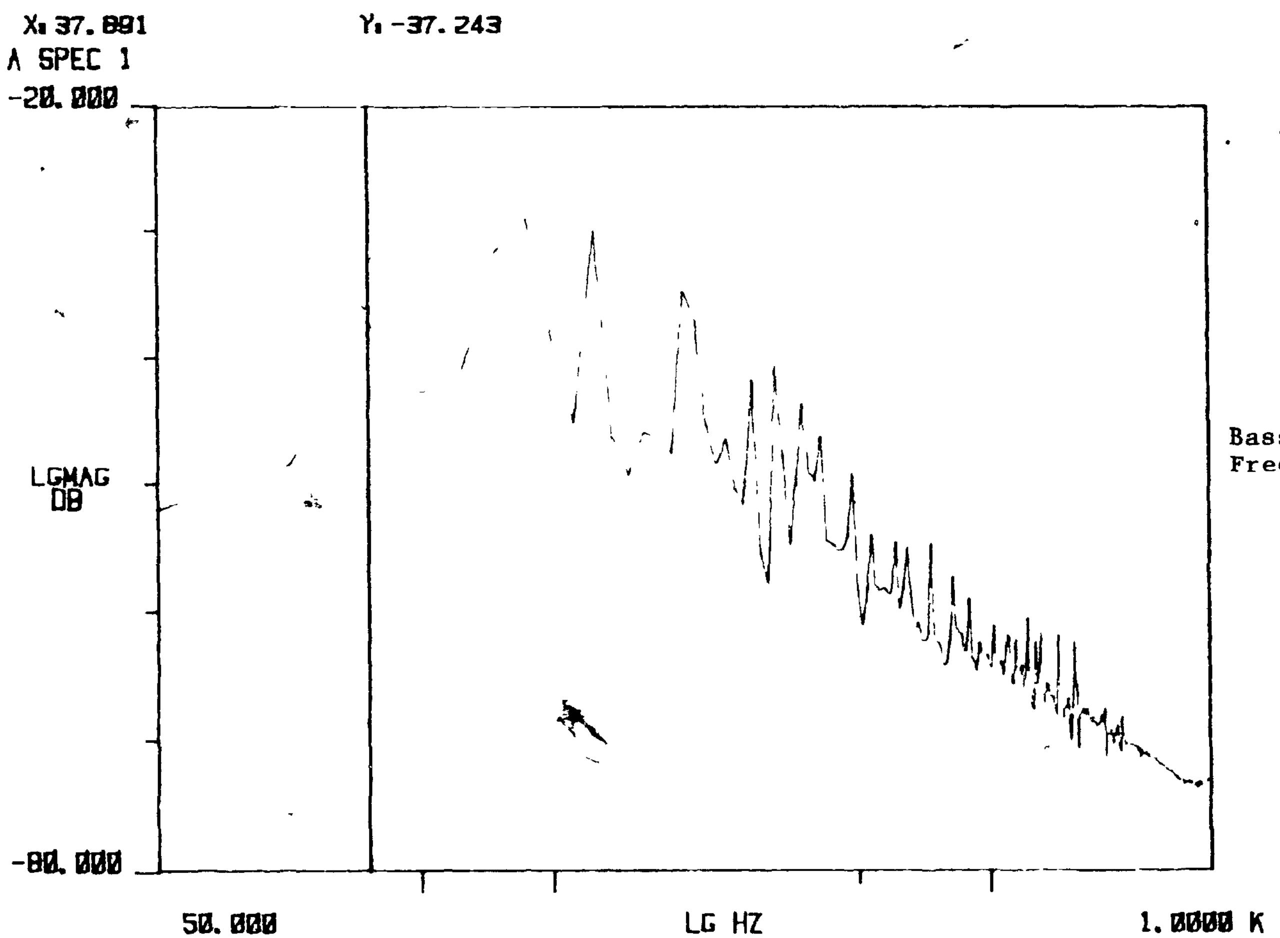
Bass Placement △3 :
Frequency Domain Analysis.


0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Red - 37.8Hz.
Green - 88Hz.
Blue - 125Hz.
Black - 163Hz.

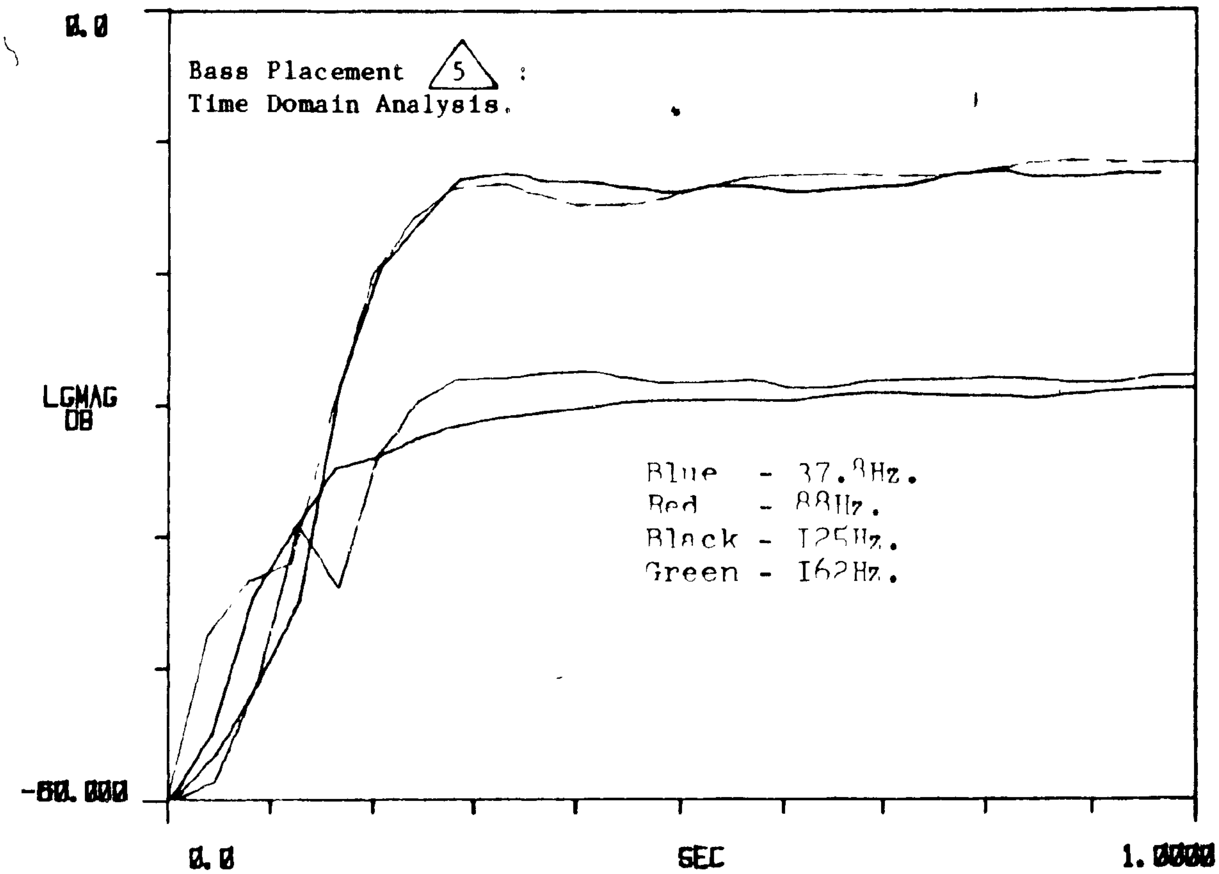

0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000
Bass Placement 3 :
Time Domain Analysis.
Black - 200Hz.
Red - 250Hz.
Green - 287Hz.

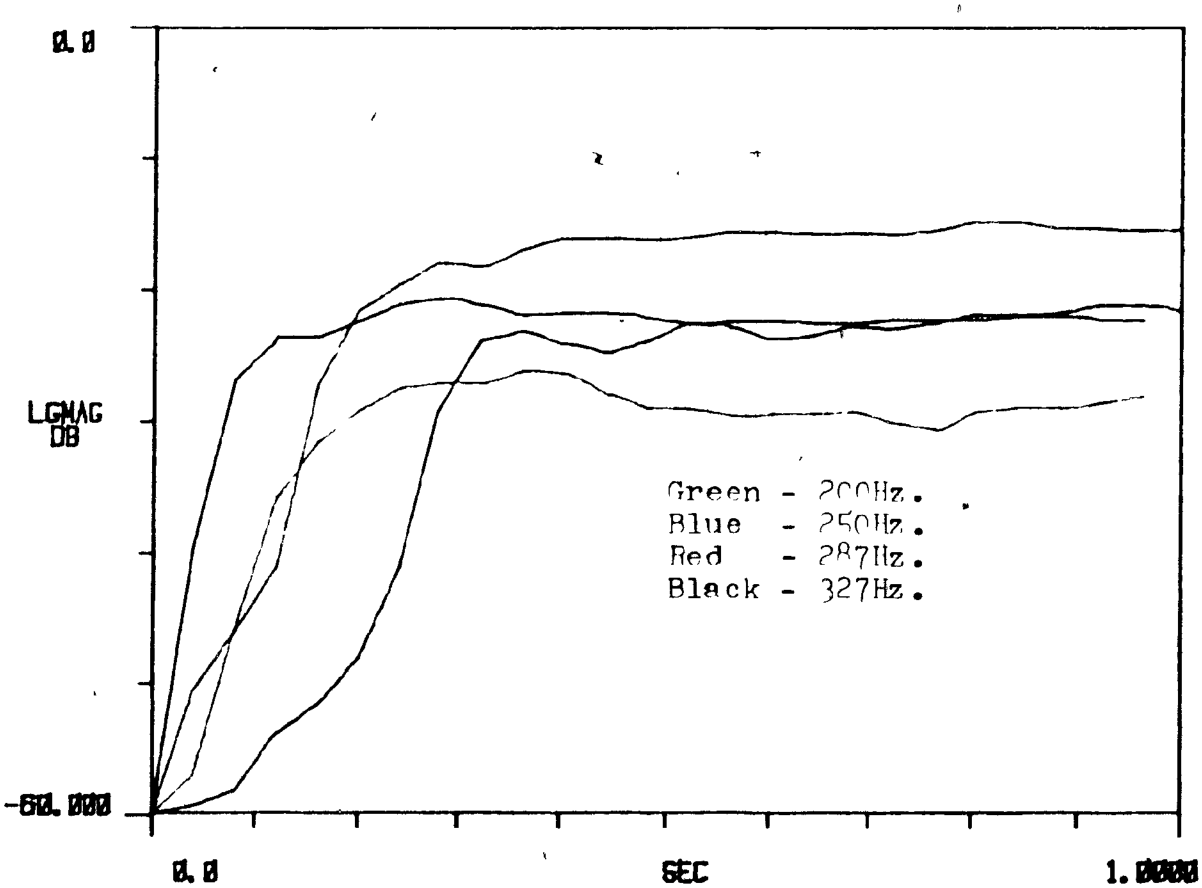


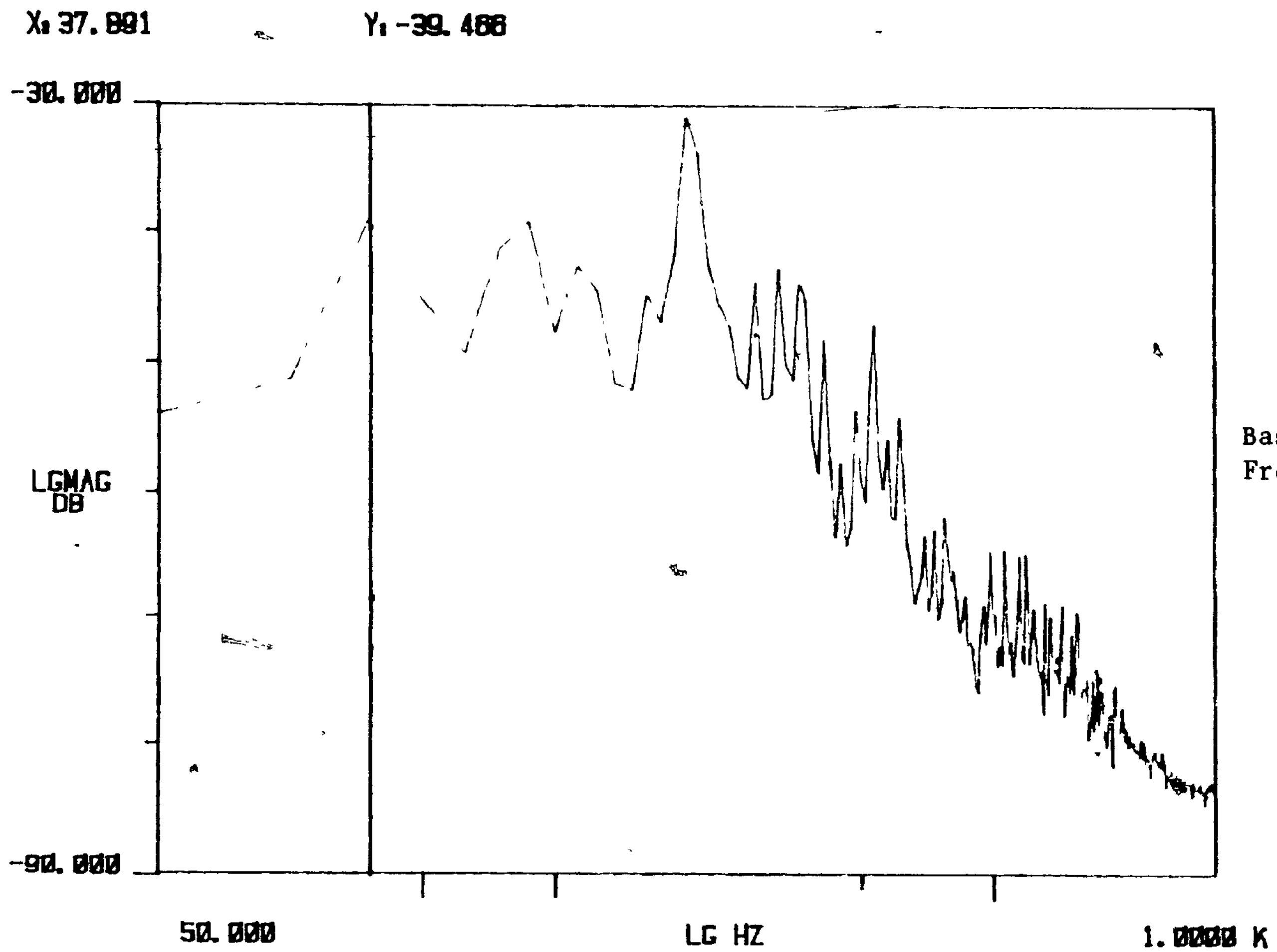
Bass Placement 4 :
Frequency Domain Analysis.



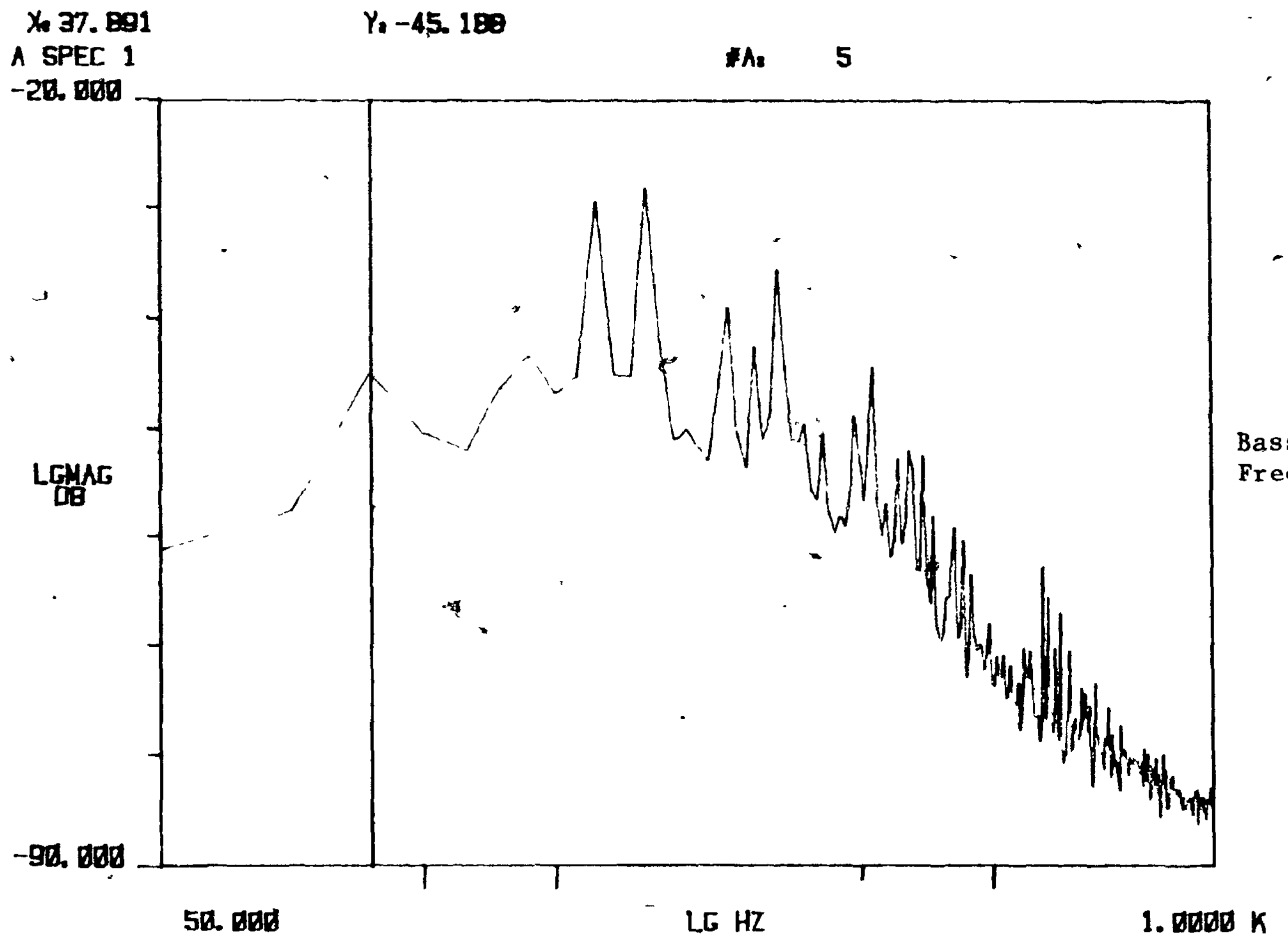
Bass Placement (5): Frequency Domain Analysis.


0.0
Bass Placement 5 :
Time Domain Analysis.
LGMAG
DB
Blue - 37.8Hz.
Red - 88Hz.
Black - I25Hz.
Green - I62Hz.
-60.000
0.0
SEC
1.0000


0.0
LGMAG
DB
Green - 200Hz.
Blue - 250Hz.
Red - 287Hz.
Black - 327Hz.
-60.000
0.0
SEC
1.0000

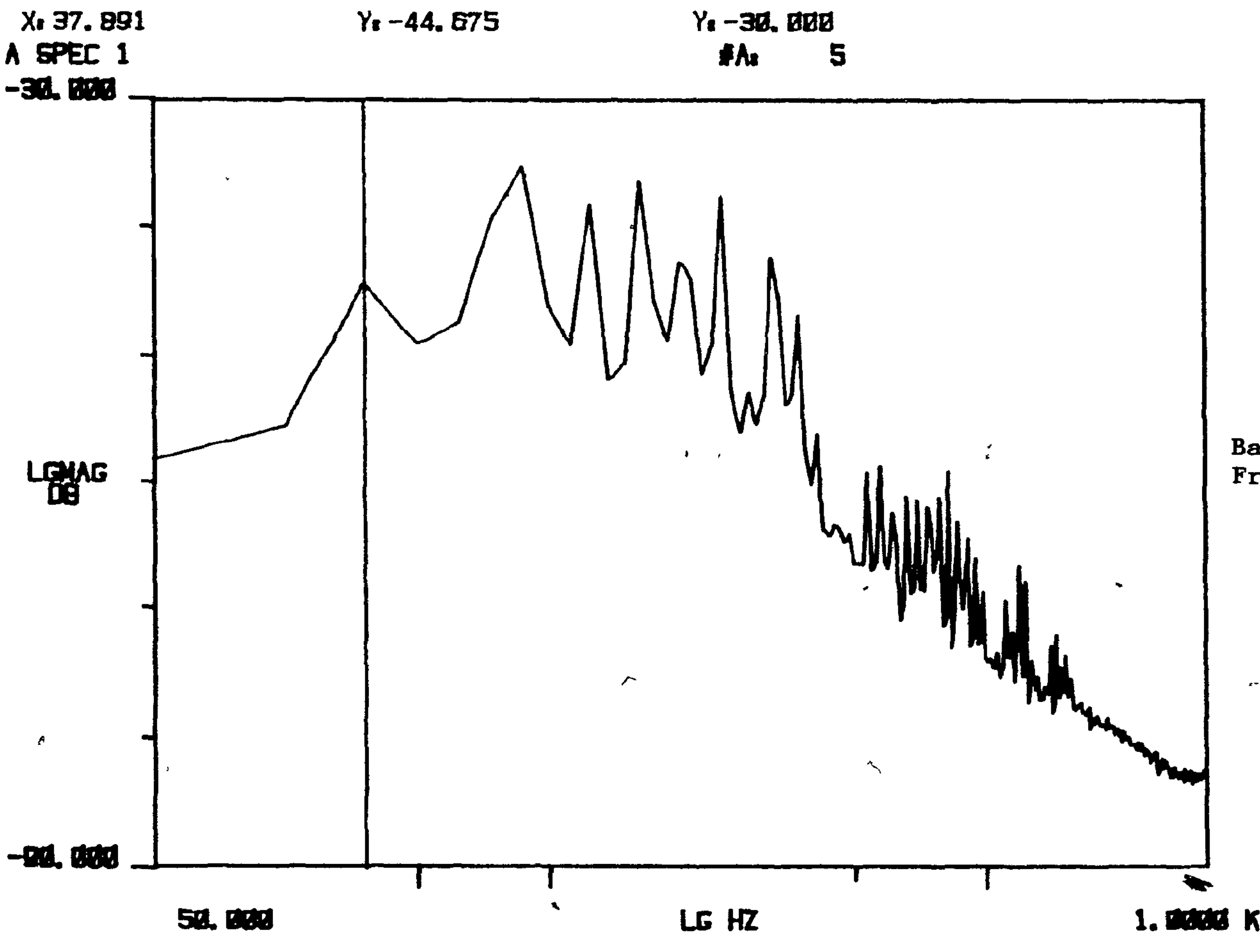


Bass Placement 6 :
Frequency Domain Analysis.

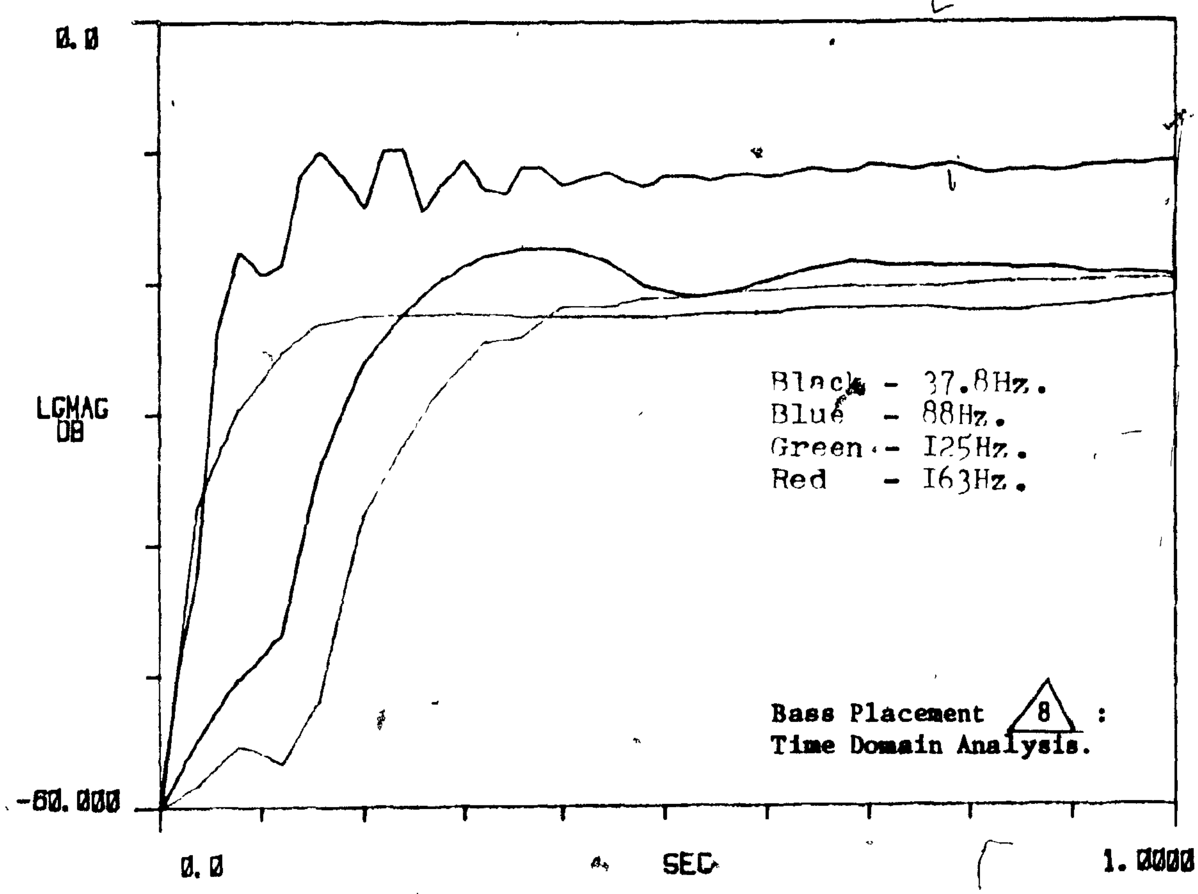


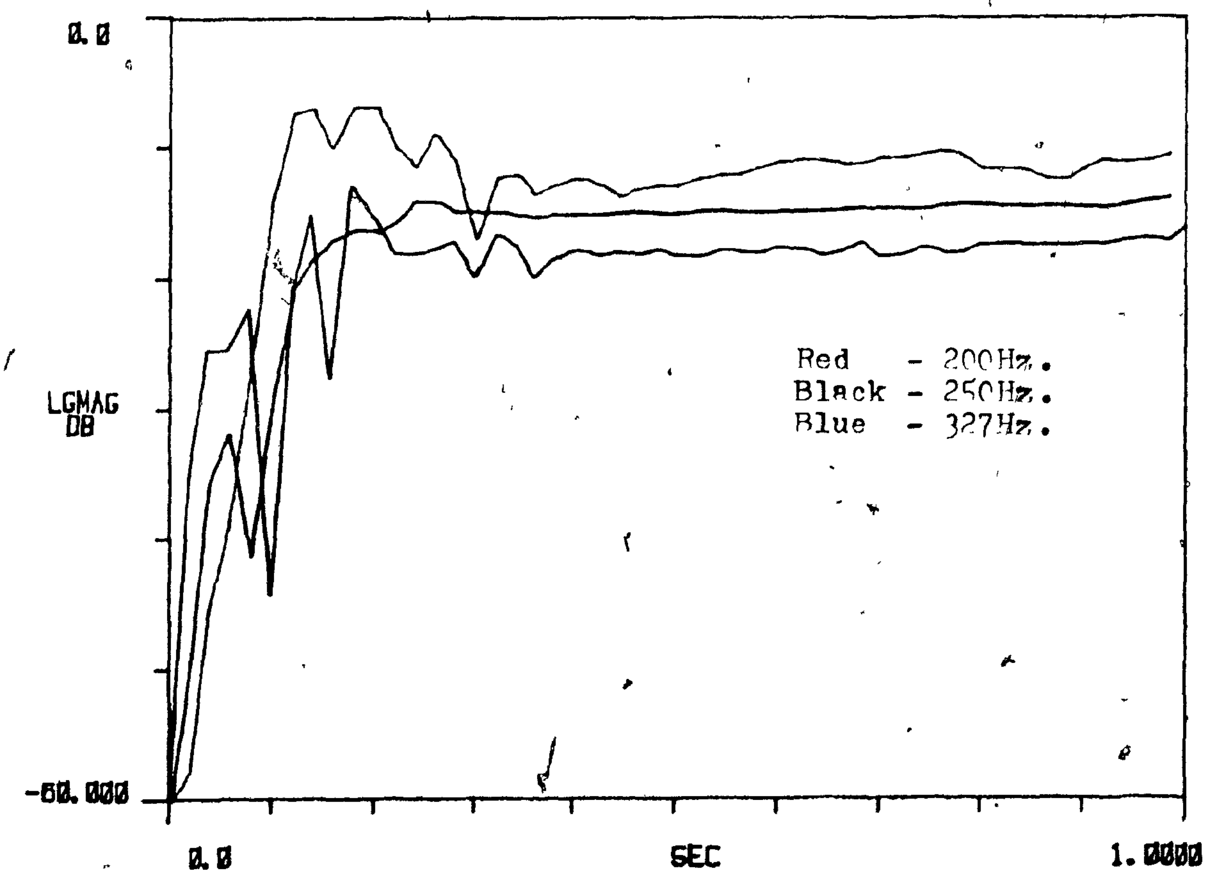
Bass Placement (7) :
Frequency Domain Analysis.

183

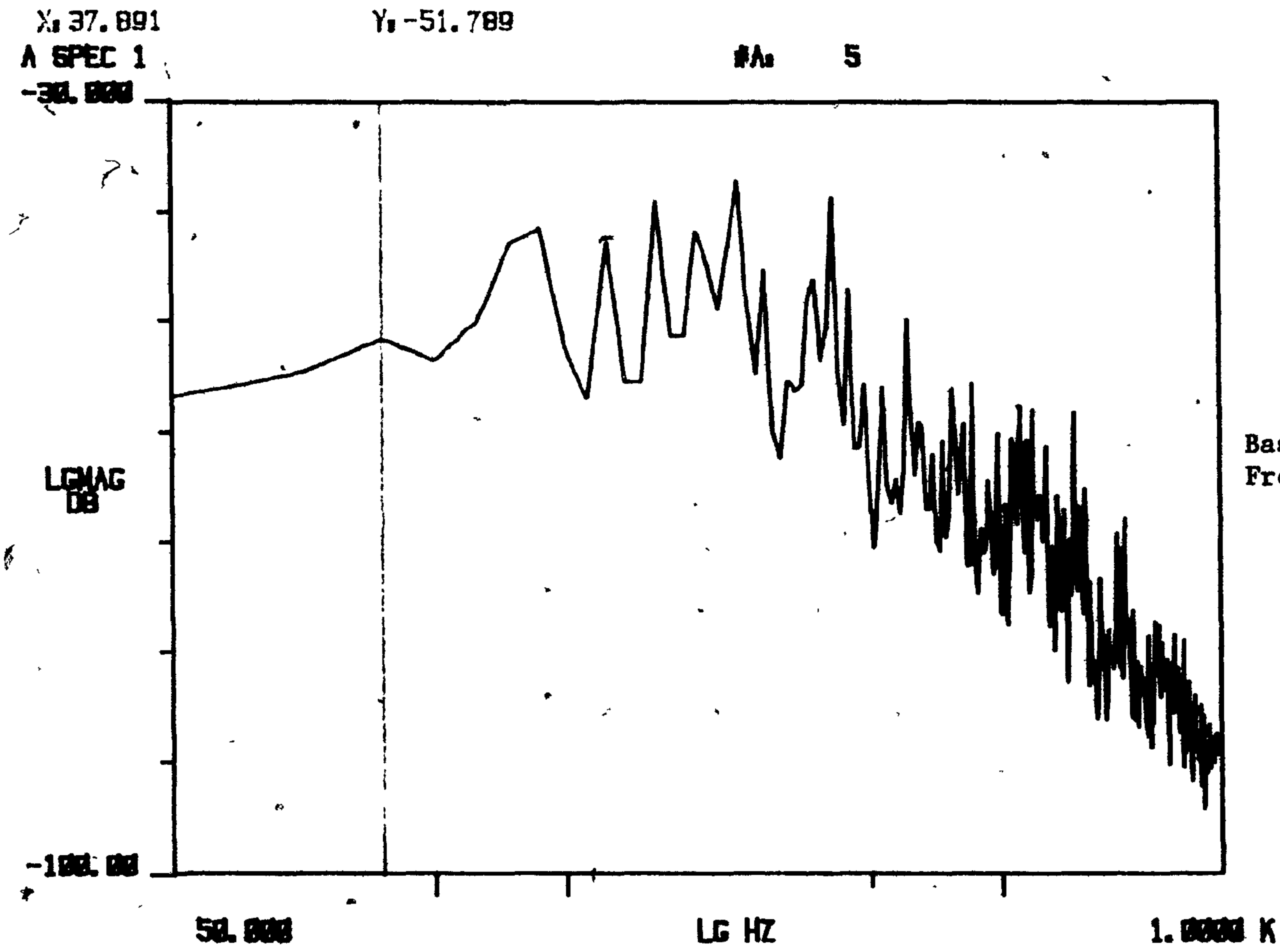


Bass Placement (8) :
Frequency Domain Analysis.

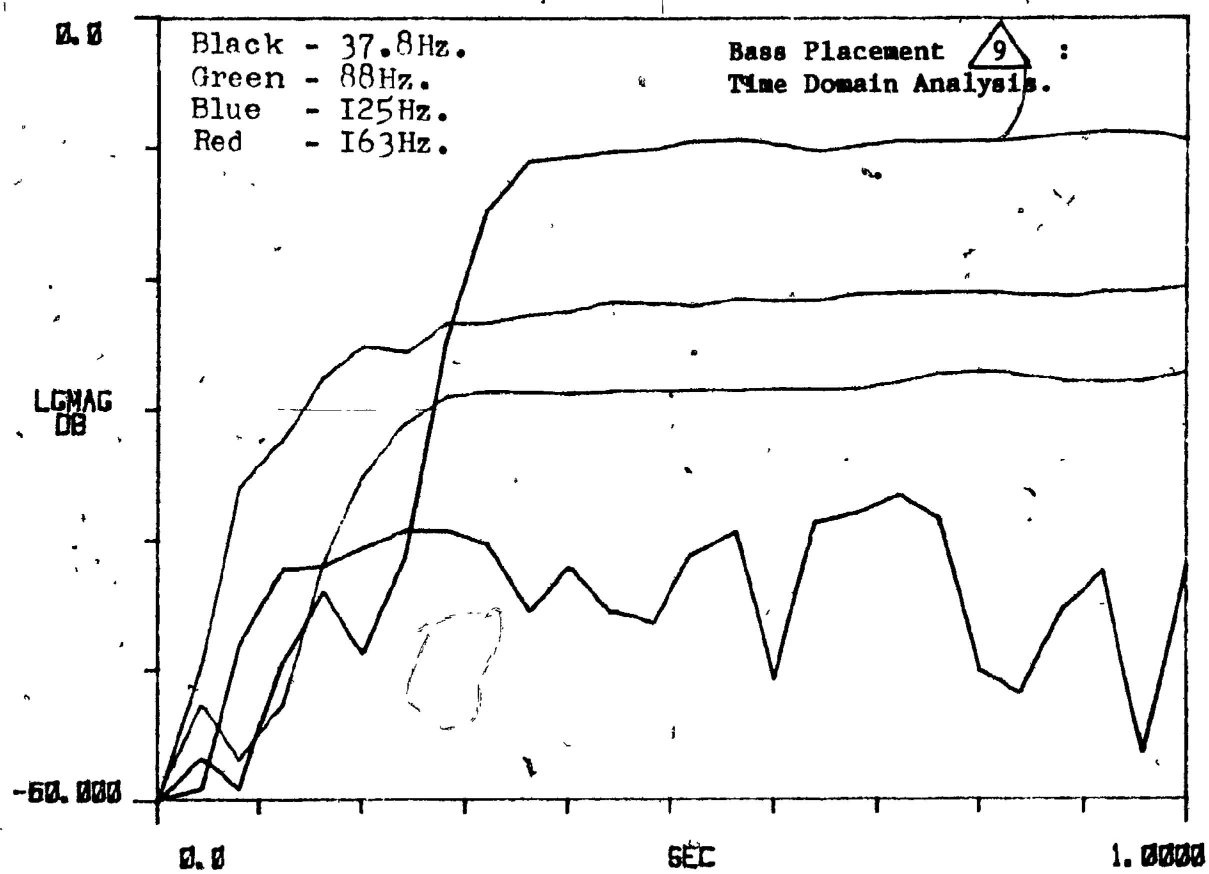

0.0
LGMAG DB
-60.000
0.0
SEC
1.0000
Black - 37.8Hz.
Blue - 88Hz.
Green - 125Hz.
Red - 163Hz.
Bass Placement 8 :
Time Domain Analysis.

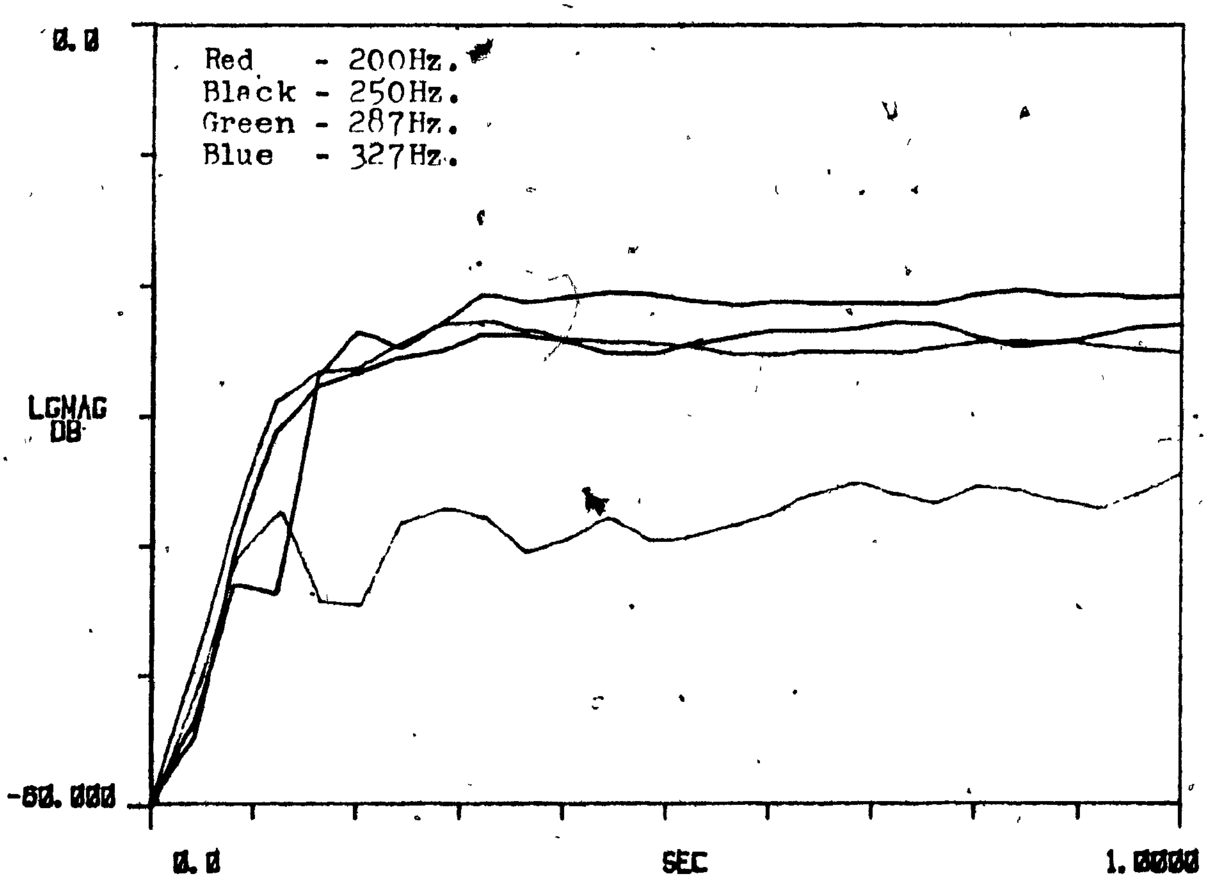

0.0
LGMAG DB
-60.000
0.0
SEC
1.0000
Red - 200Hz.
Black - 250Hz.
Blue - 327Hz.

185



Bass Placement (9) : Frequency Domain Analysis.

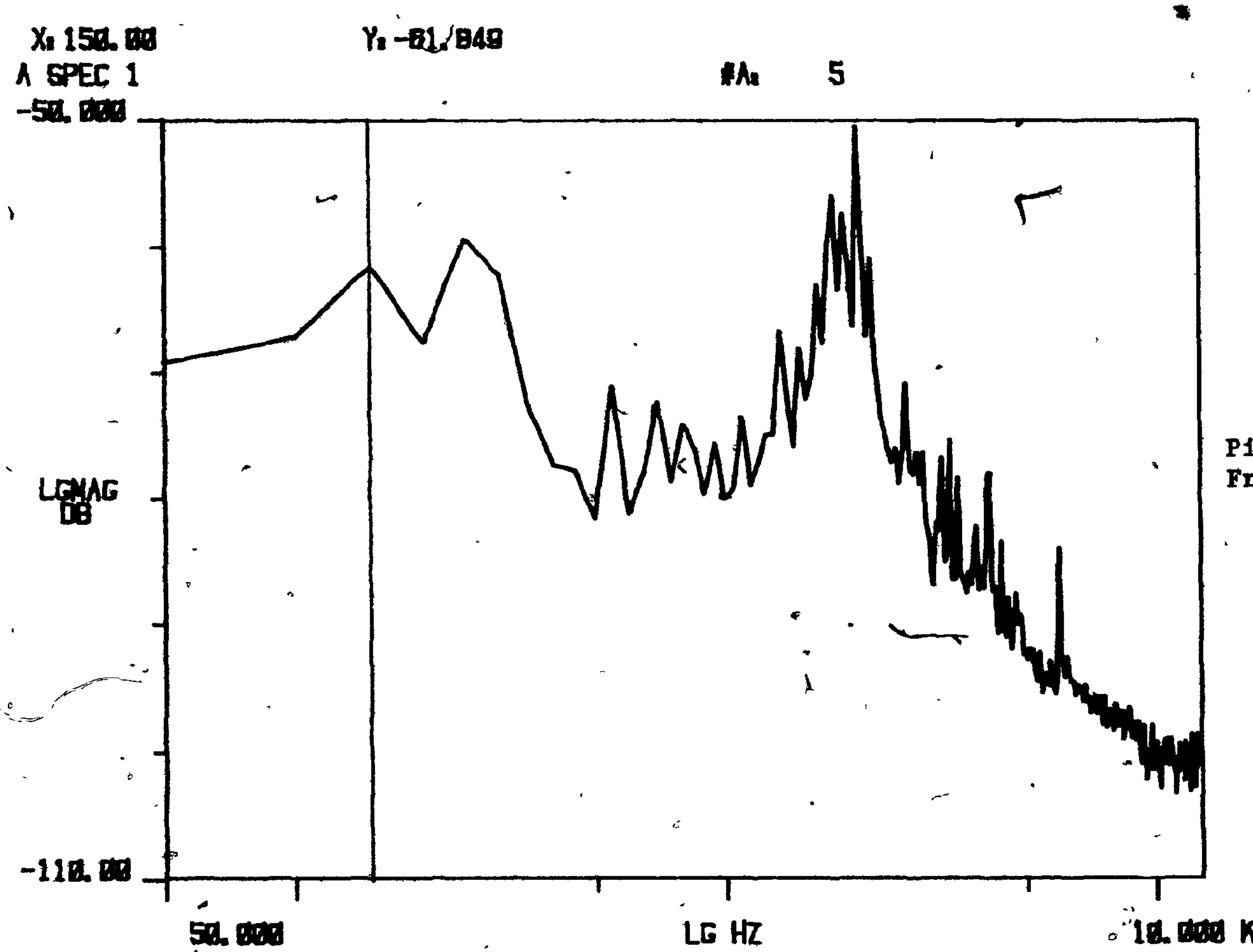

0.0
Black - 37.8Hz.
Green - 88Hz.
Blue - I25Hz.
Red - I63Hz.
Bass Placement 9 :
Time Domain Analysis.
LGMAG
DB
-60.000
0.0
SEC
1.0000


0.0
Red - 200Hz.
Black - 250Hz.
Green - 287Hz.
Blue - 327Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

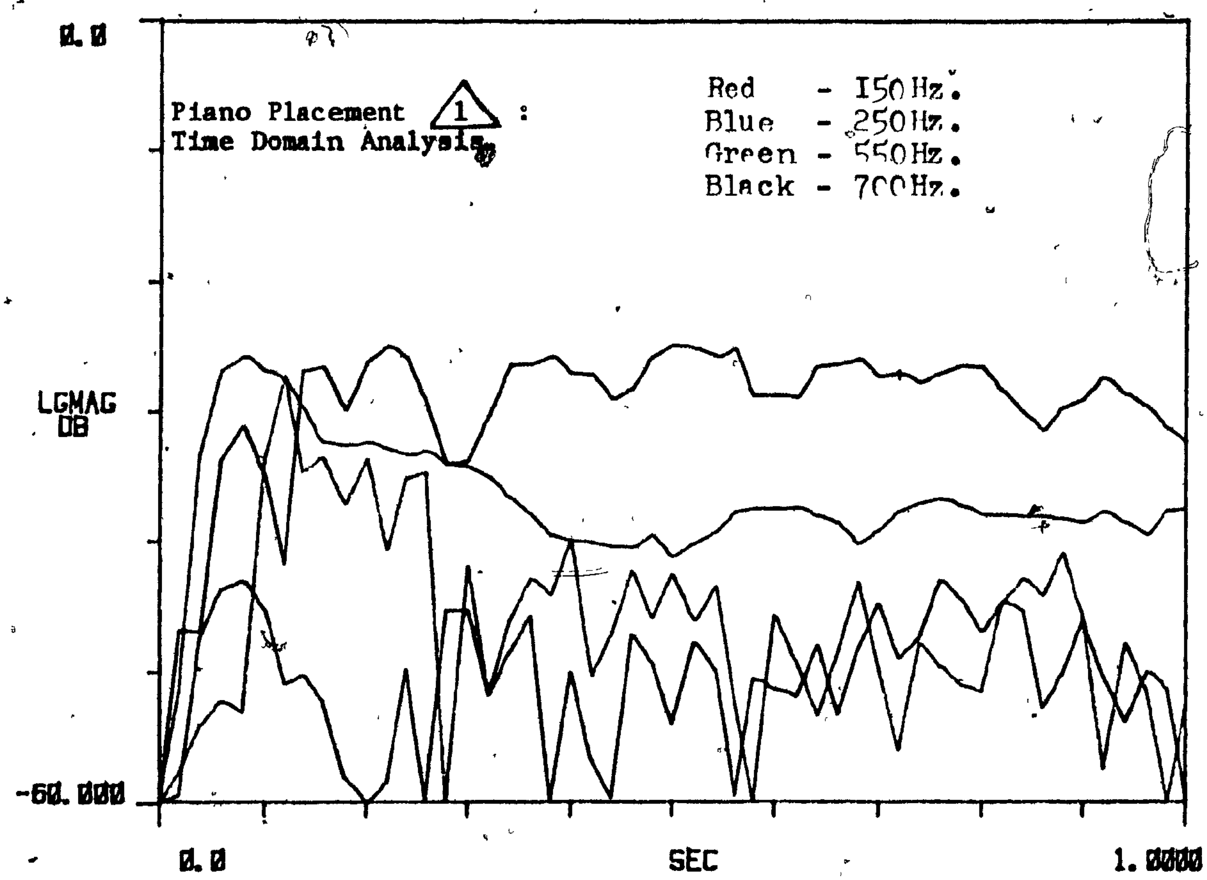
APPENDIX V

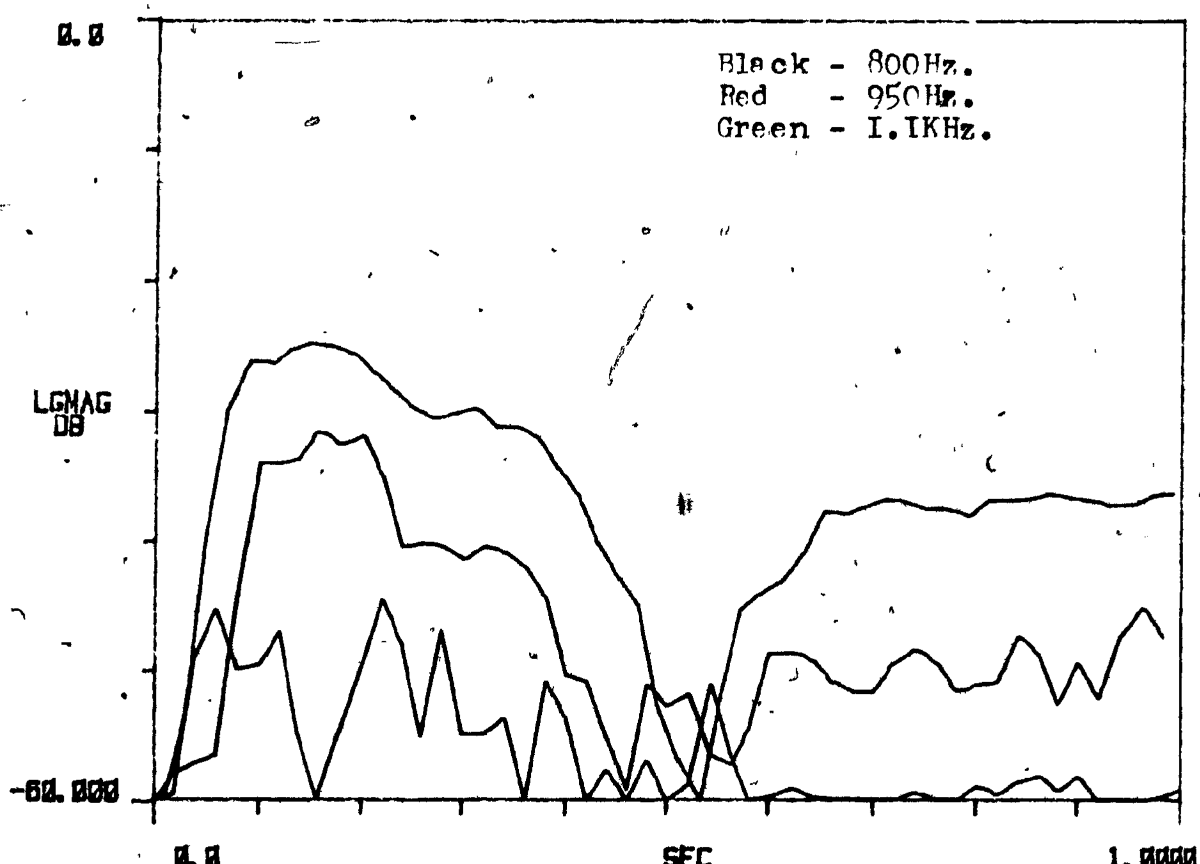
Piano

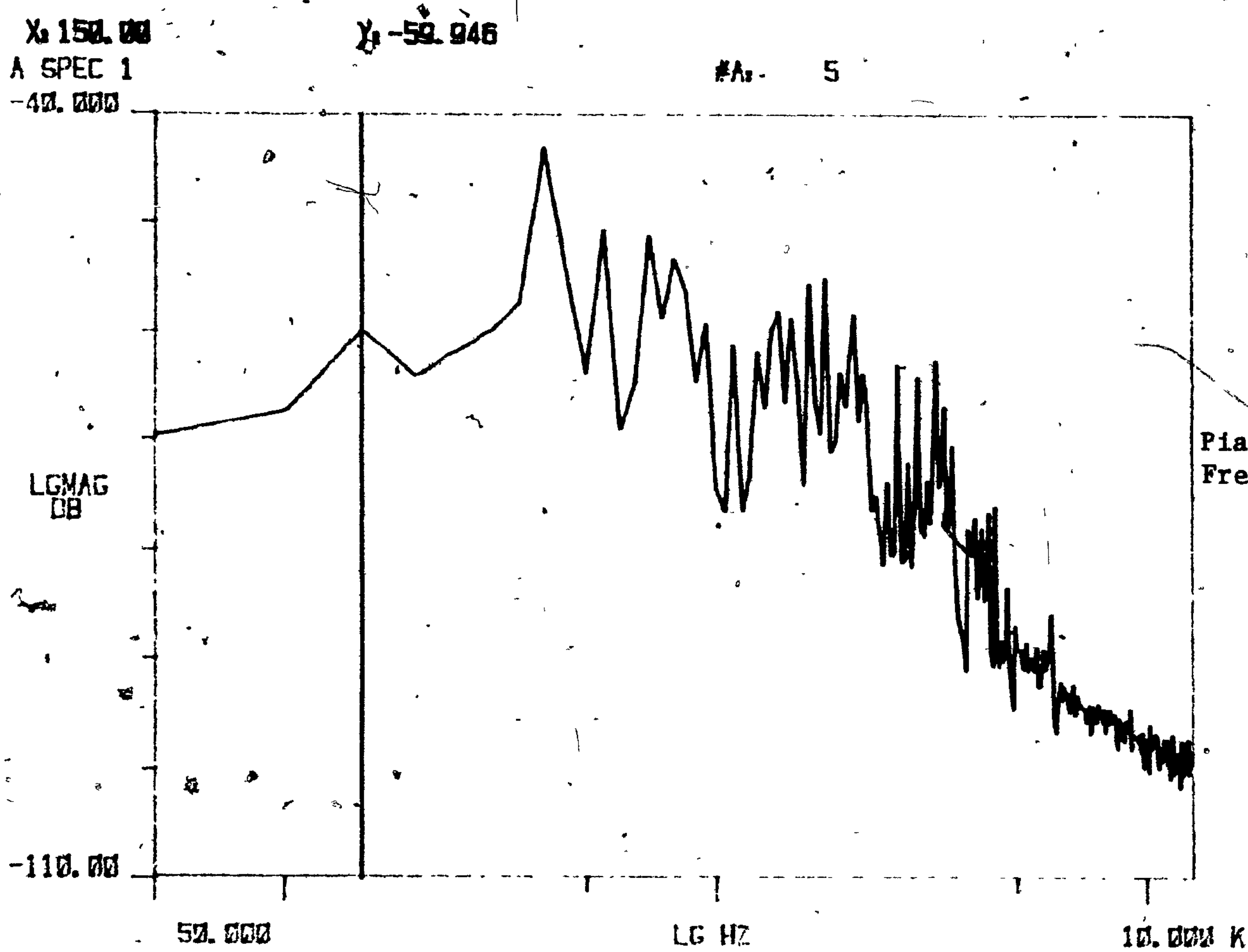
Spectrum Analysis



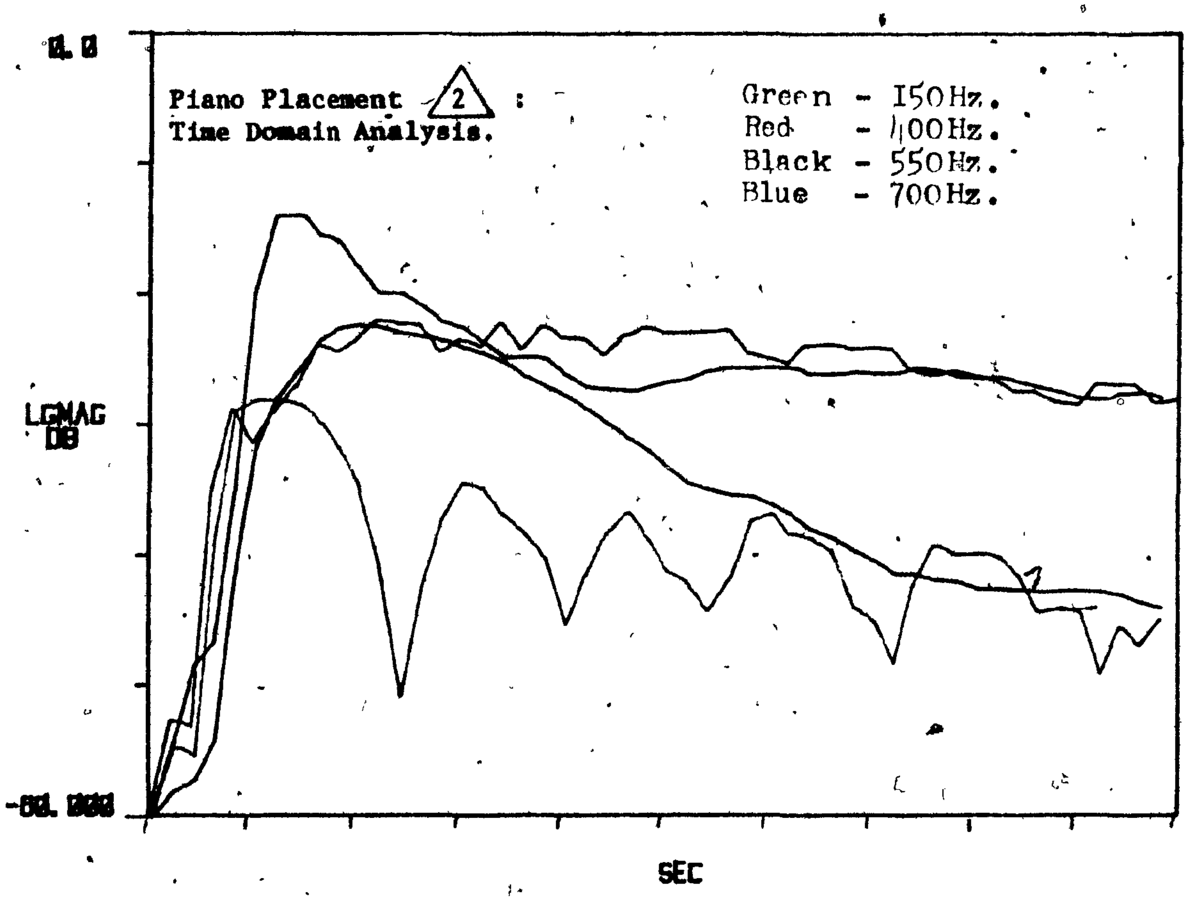
Piano Placement △1 :
Frequency Domain Analysis.

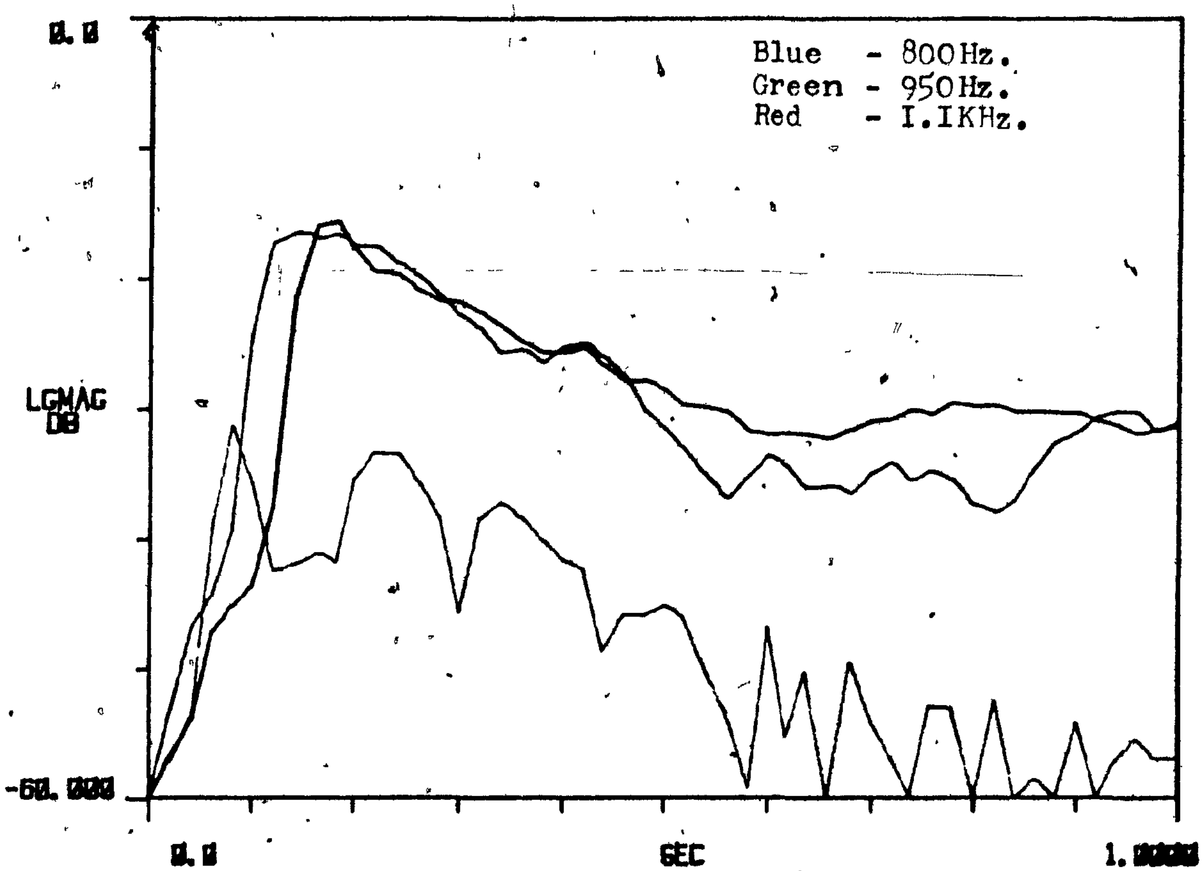

0.0
Piano Placement 1 :
Time Domain Analysis
Red - 150Hz.
Blue - 250Hz.
Green - 550Hz.
Black - 700Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000


0.0
Black - 800Hz.
Red - 950Hz.
Green - 1.1KHz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

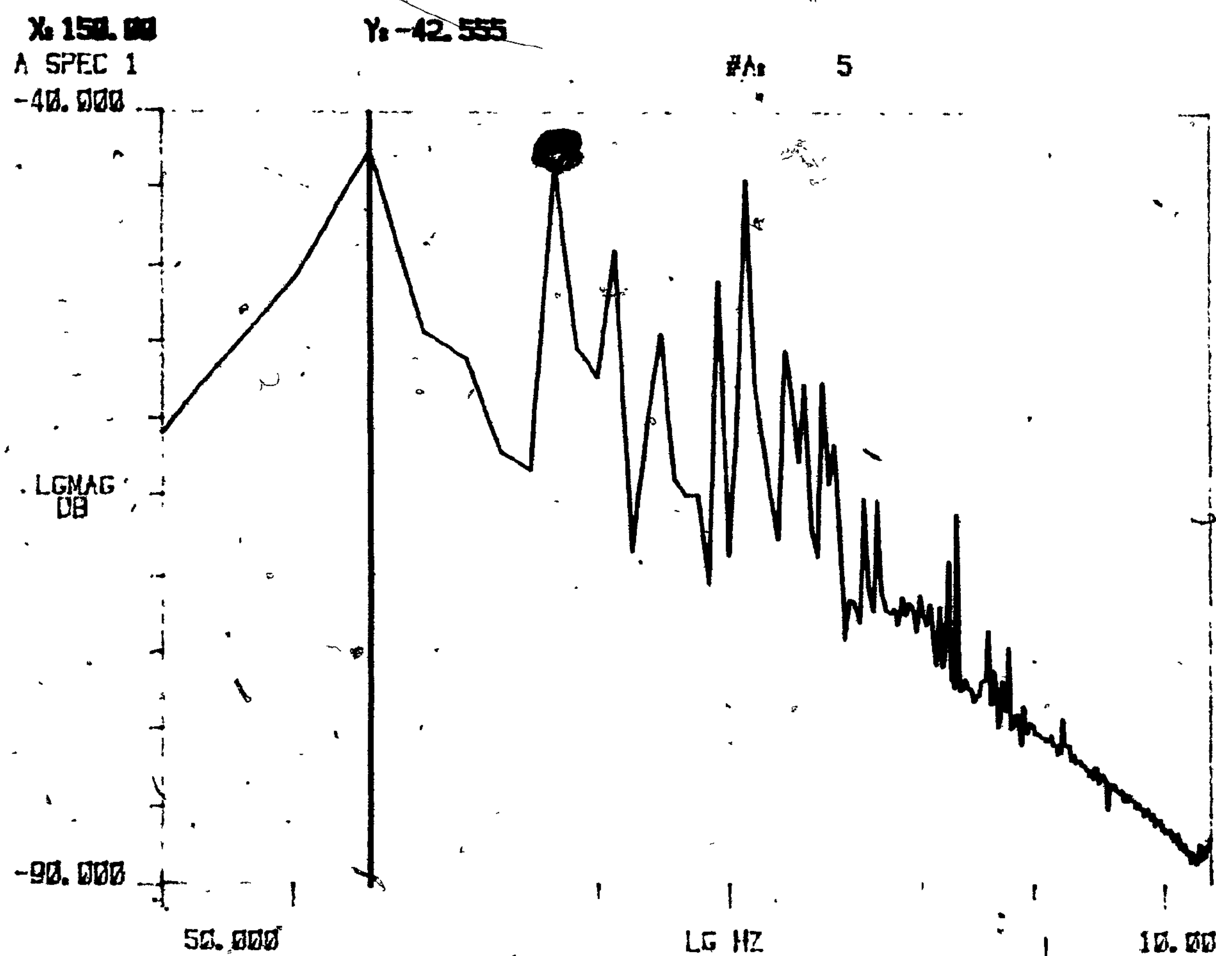


Piano Placement (2) :
Frequency Domain Analysis.

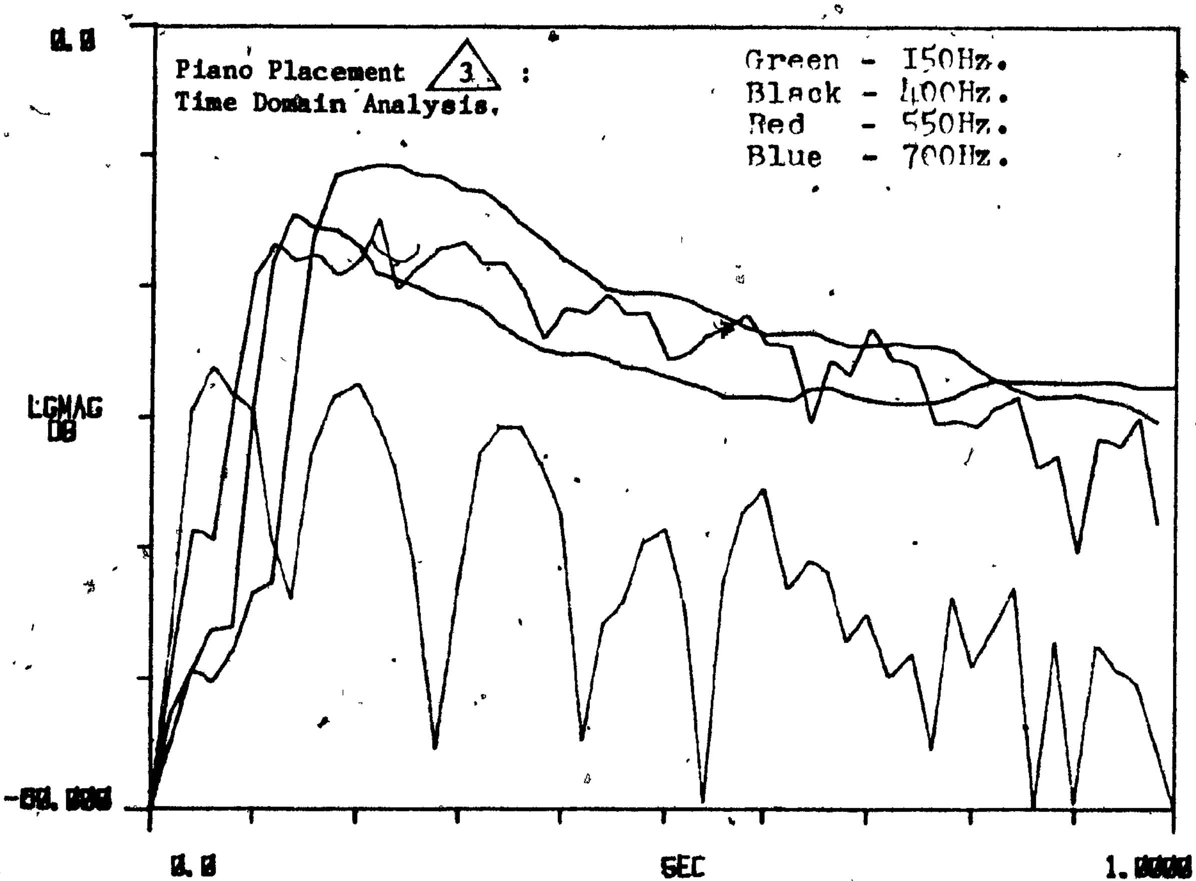

Piano Placement 2 :
Time Domain Analysis.
Green - 150Hz.
Red - 400Hz.
Black - 550Hz.
Blue - 700Hz.
0.0
LGMAG DB
-60.000
SEC

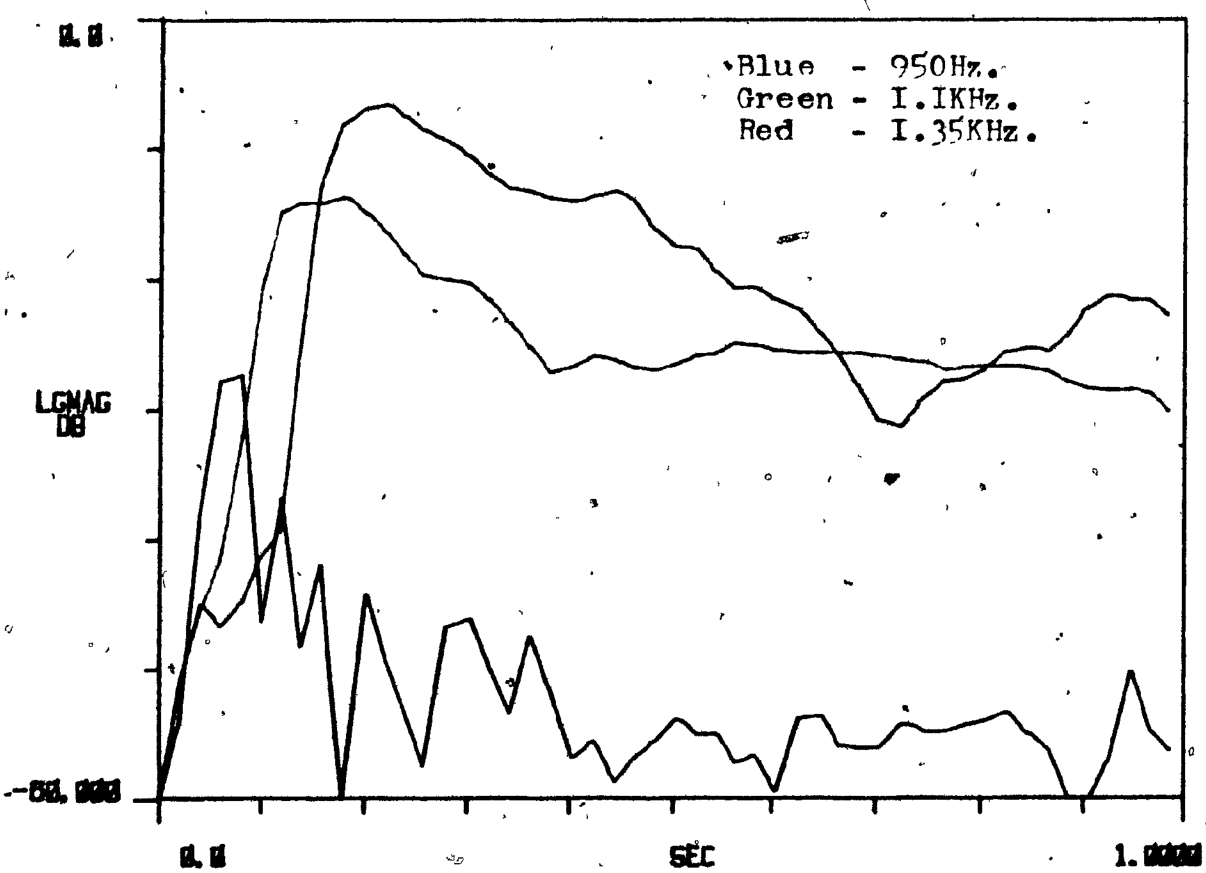

Blue - 800Hz.
Green - 950Hz.
Red - 1.1KHz.
0.0
LGMAG DB
-60.000
0.0
SEC
1.0000

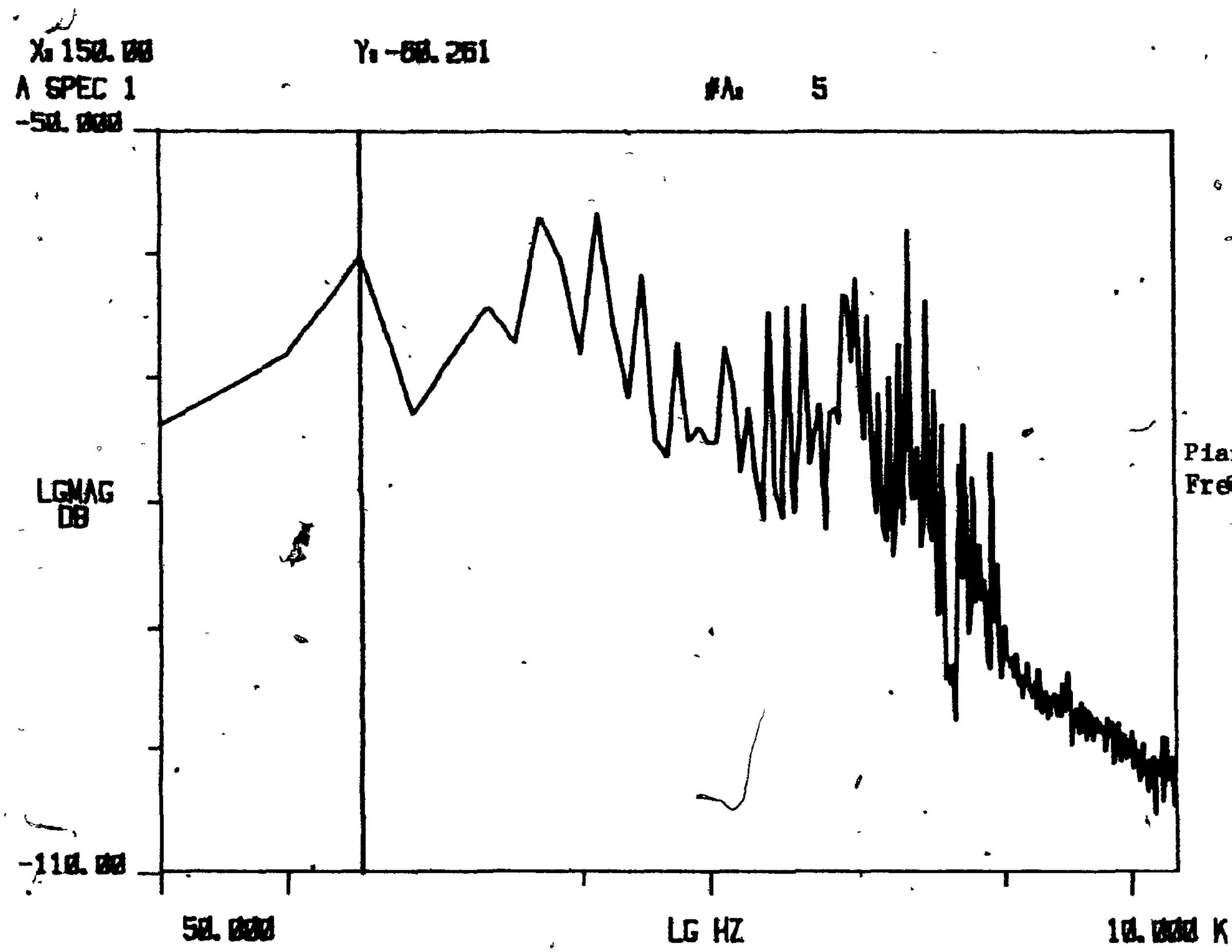
192



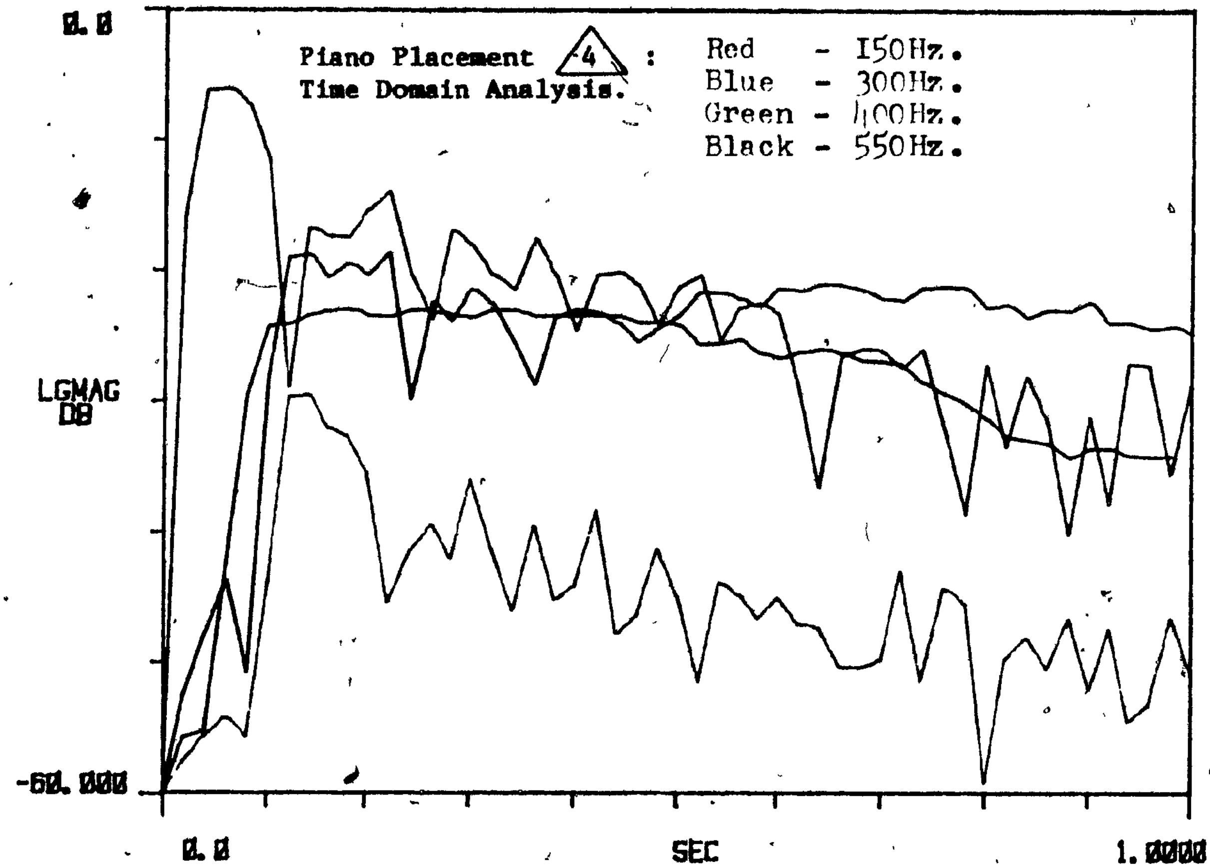
Piano Placement 3 :
Frequency Domain Analysis.

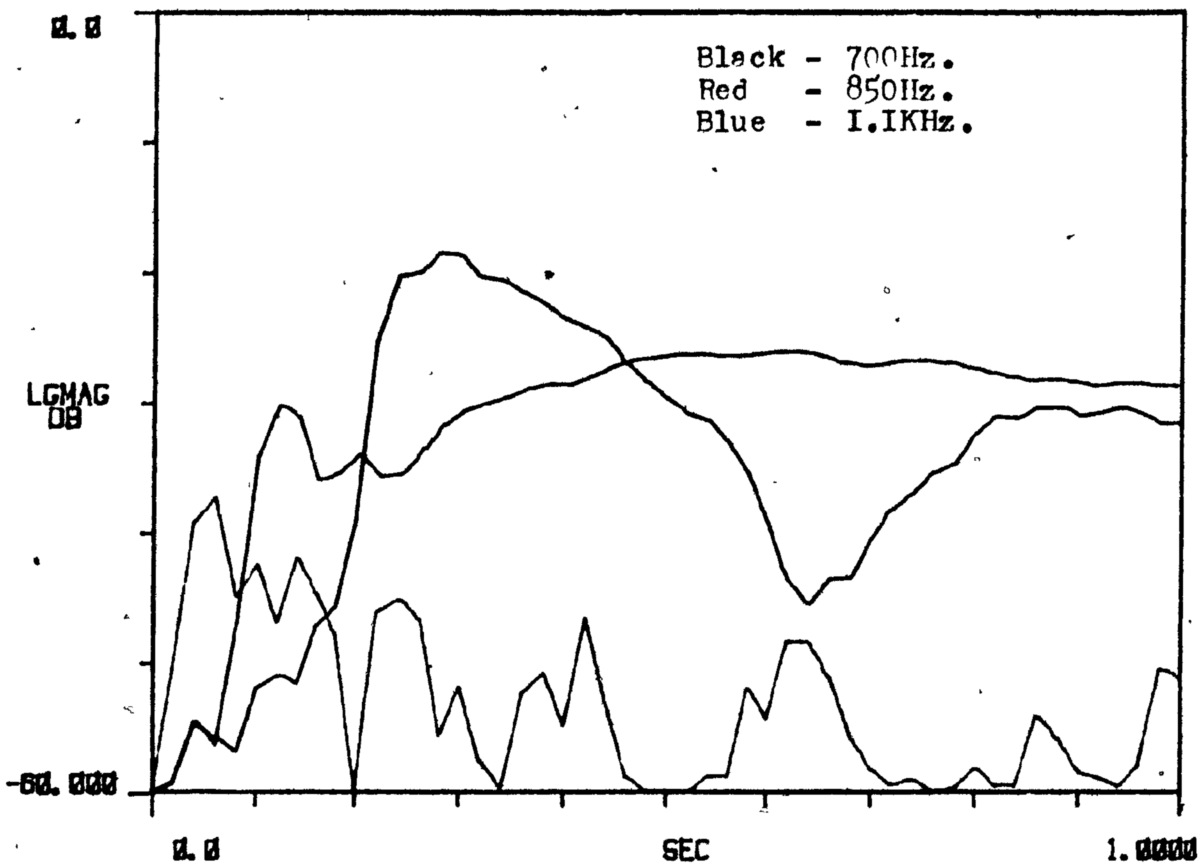

Piano Placement 3 :
Time Domain Analysis.
Green - 150Hz.
Black - 400Hz.
Red - 550Hz.
Blue - 700Hz.
LGMAG DB
SEC
1.0000

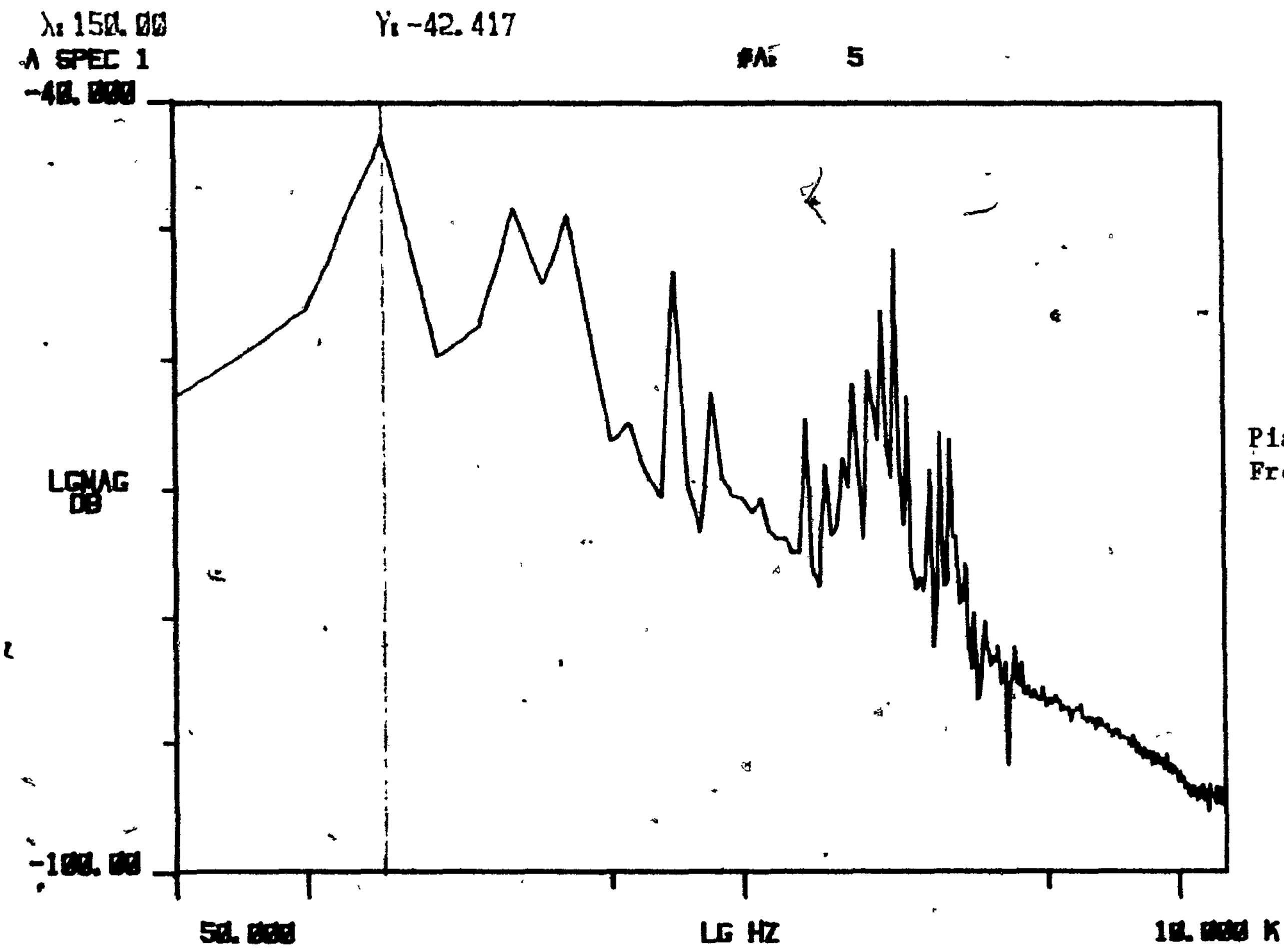

Blue - 950Hz.
Green - 1.1KHz.
Red - 1.35KHz.
LGMAG DB
SEC
1.0000



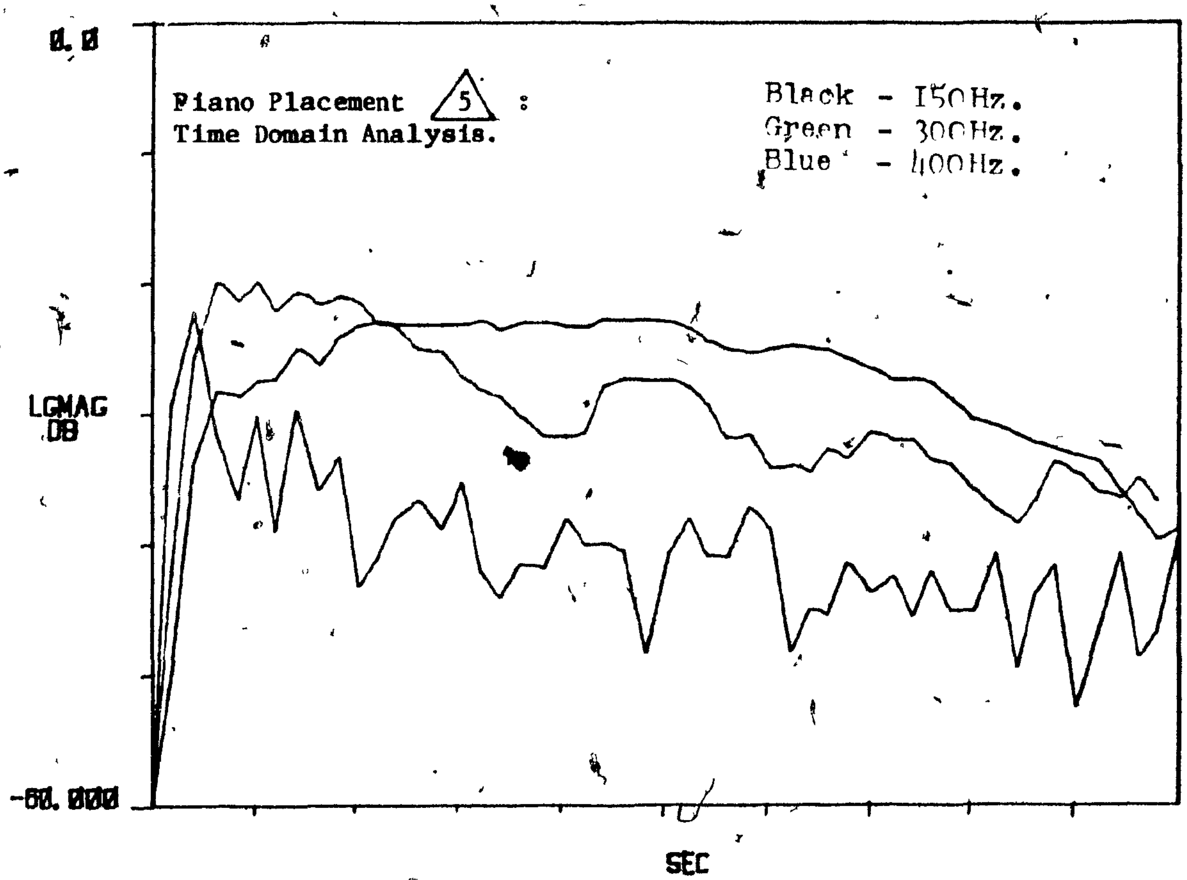
Piano Placement 4 :
Frequency Domain Analysis.

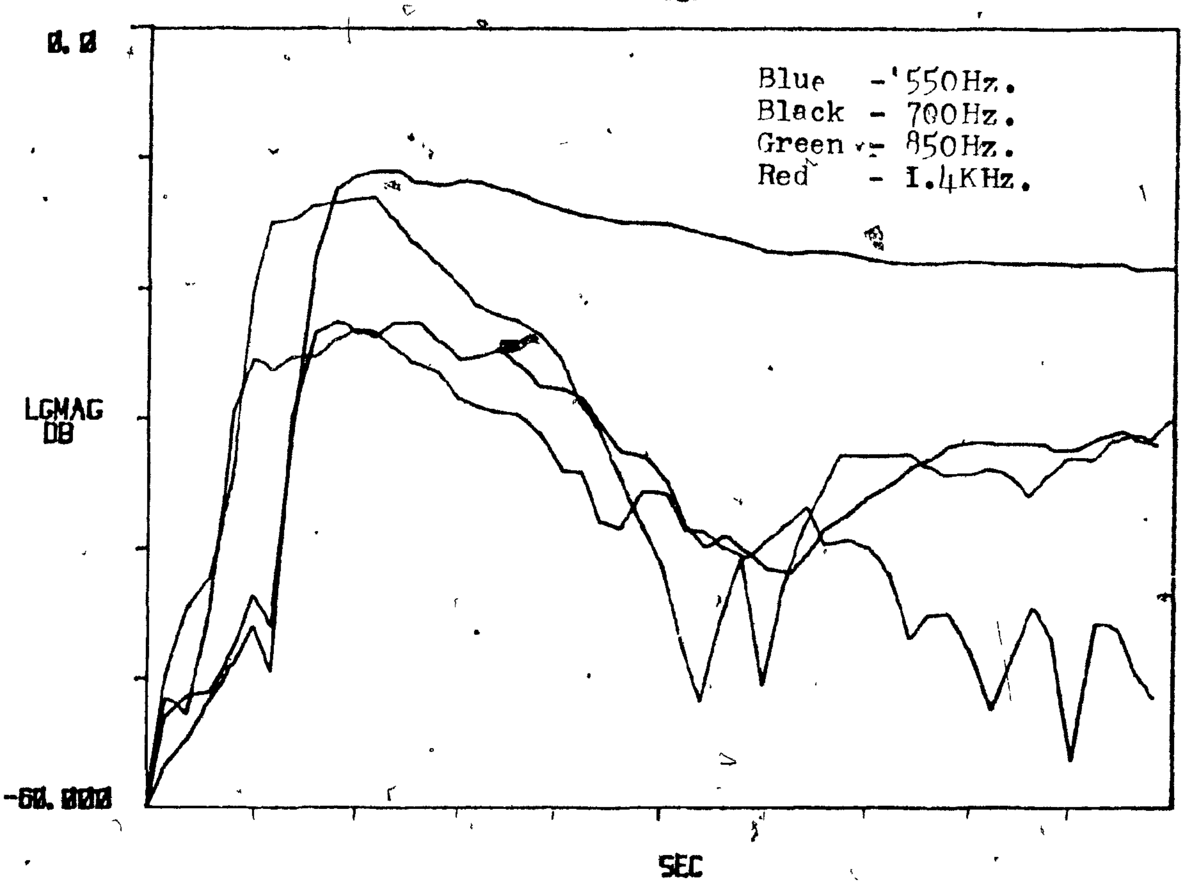

0.0
Piano Placement 4 :
Time Domain Analysis.
Red - 150Hz.
Blue - 300Hz.
Green - 400Hz.
Black - 550Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

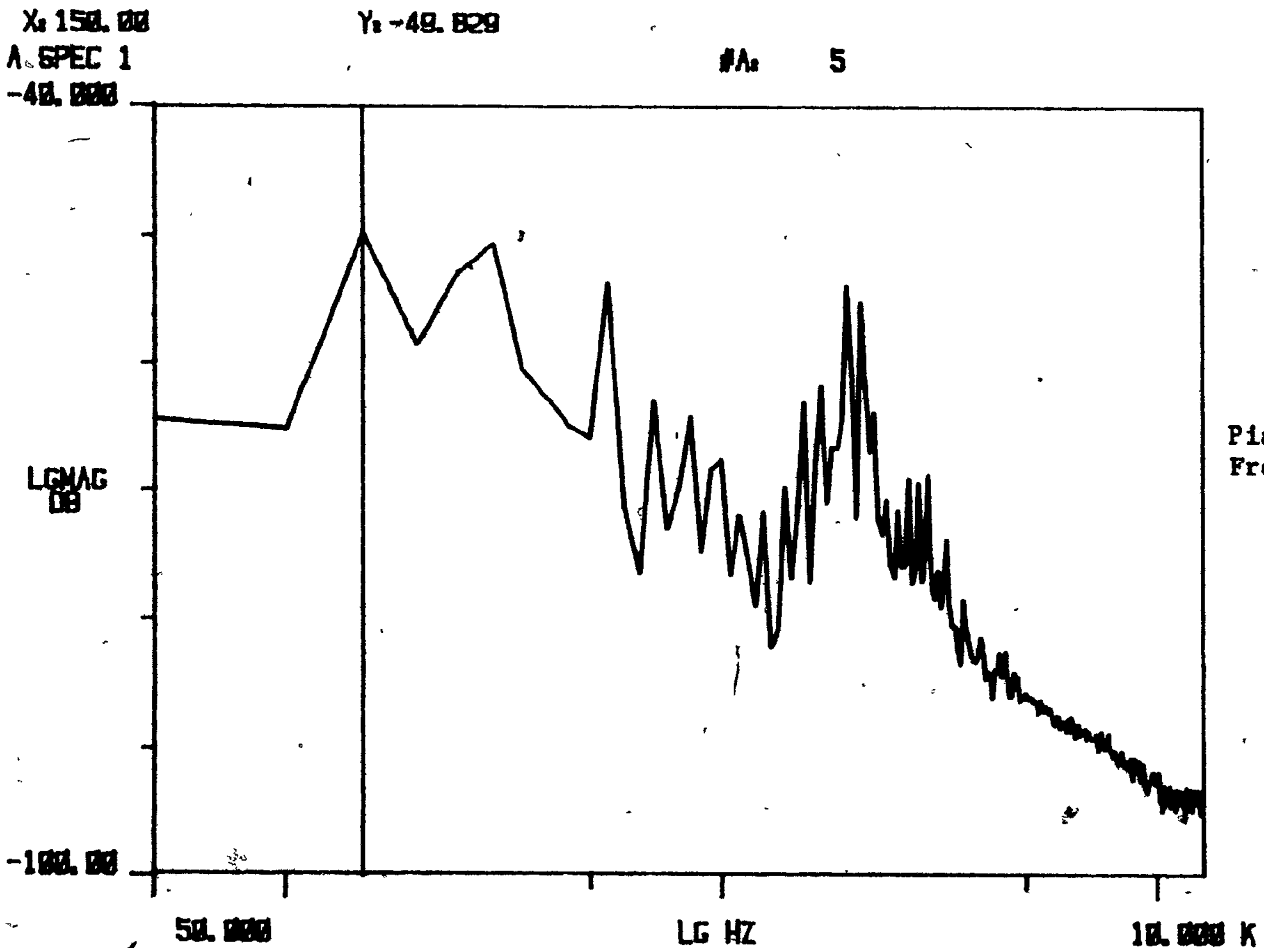

0.0
Black - 700Hz.
Red - 850Hz.
Blue - I.IKHz.
LGMAG
DB
-60.000
0.0
SEC
1.0000



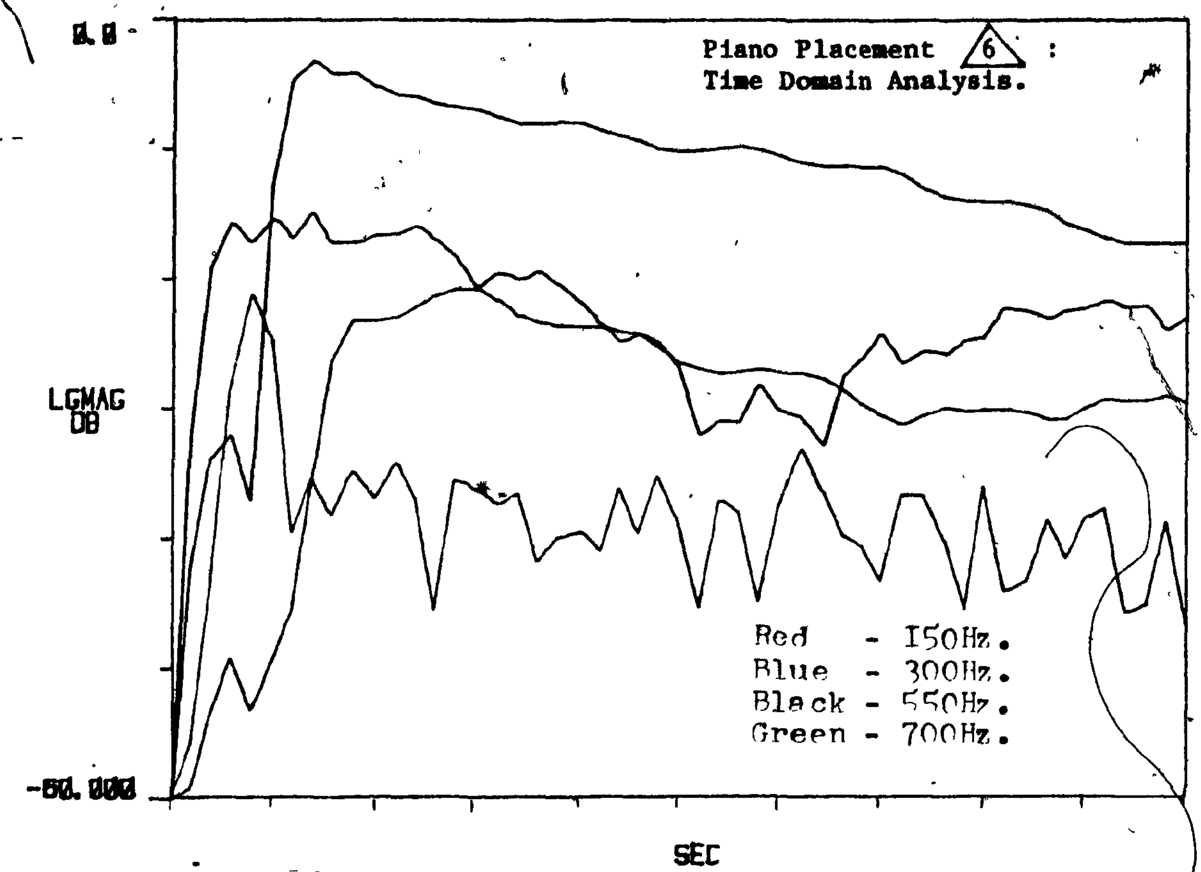
Piano Placement 5: Frequency Domain Analysis.

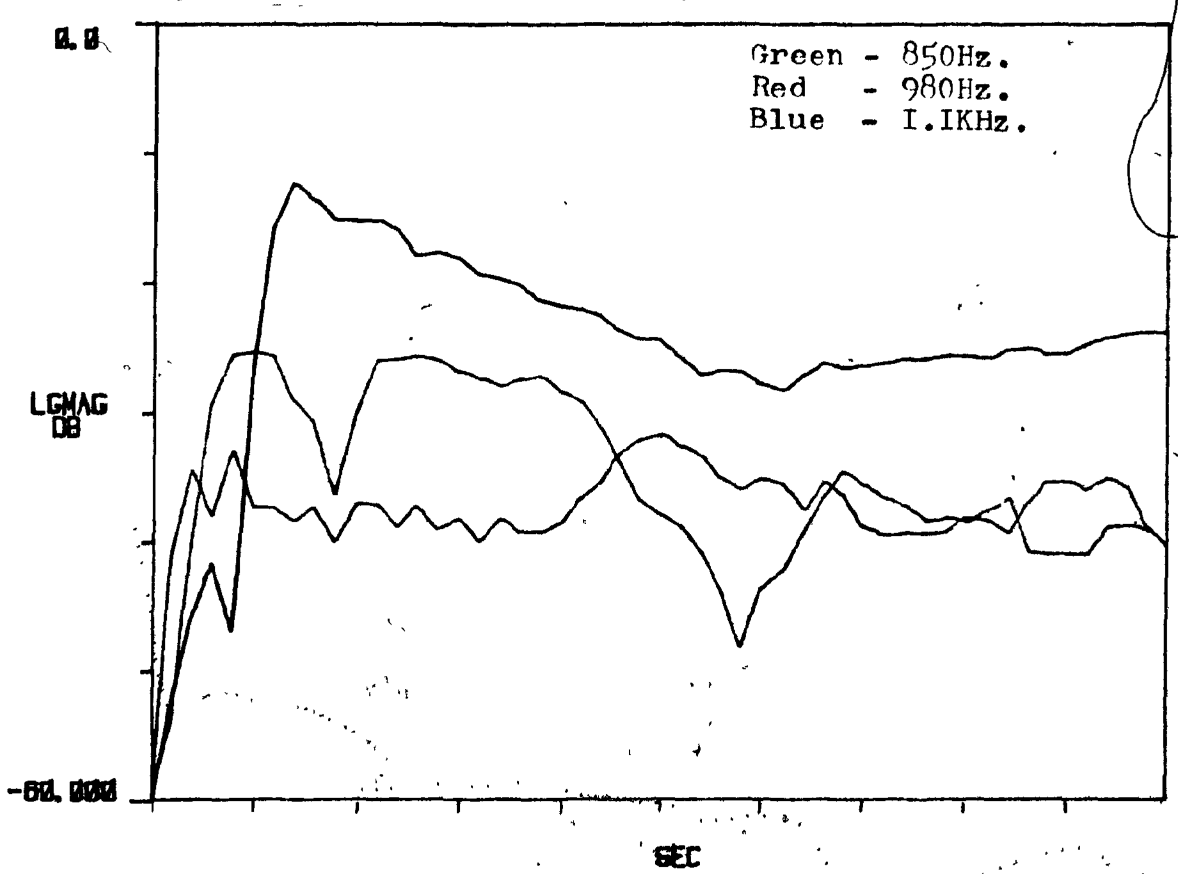

0.0
Piano Placement 5 :
Time Domain Analysis.
Black - 150Hz.
Green - 300Hz.
Blue - 400Hz.
LGMAG
DB
-60.000
SEC

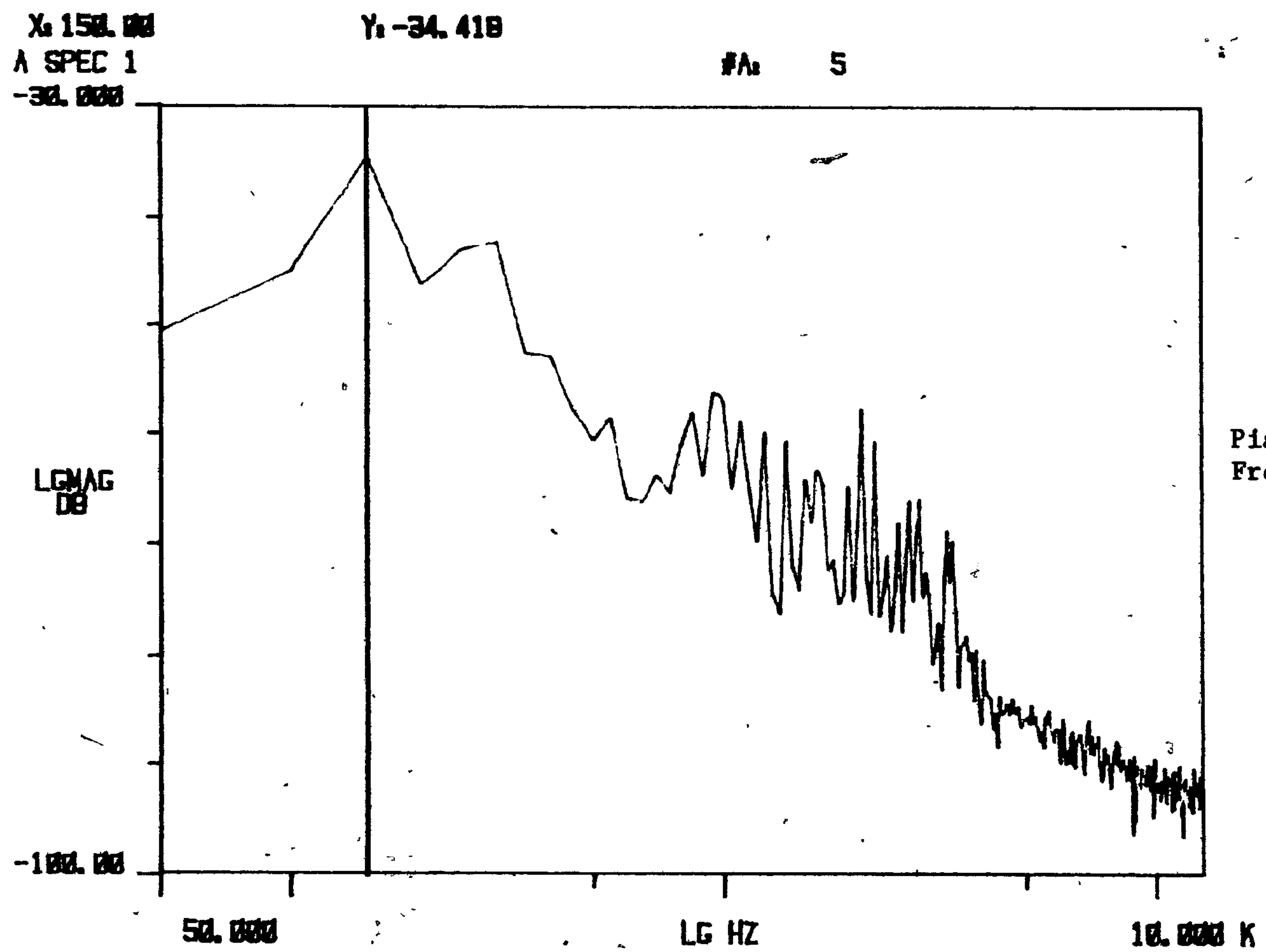

0.0
Blue - 550Hz.
Black - 700Hz.
Green - 850Hz.
Red - 1.4KHz.
LGMAG
DB
-60.000
SEC



Piano Placement (6) :
Frequency Domain Analysis.

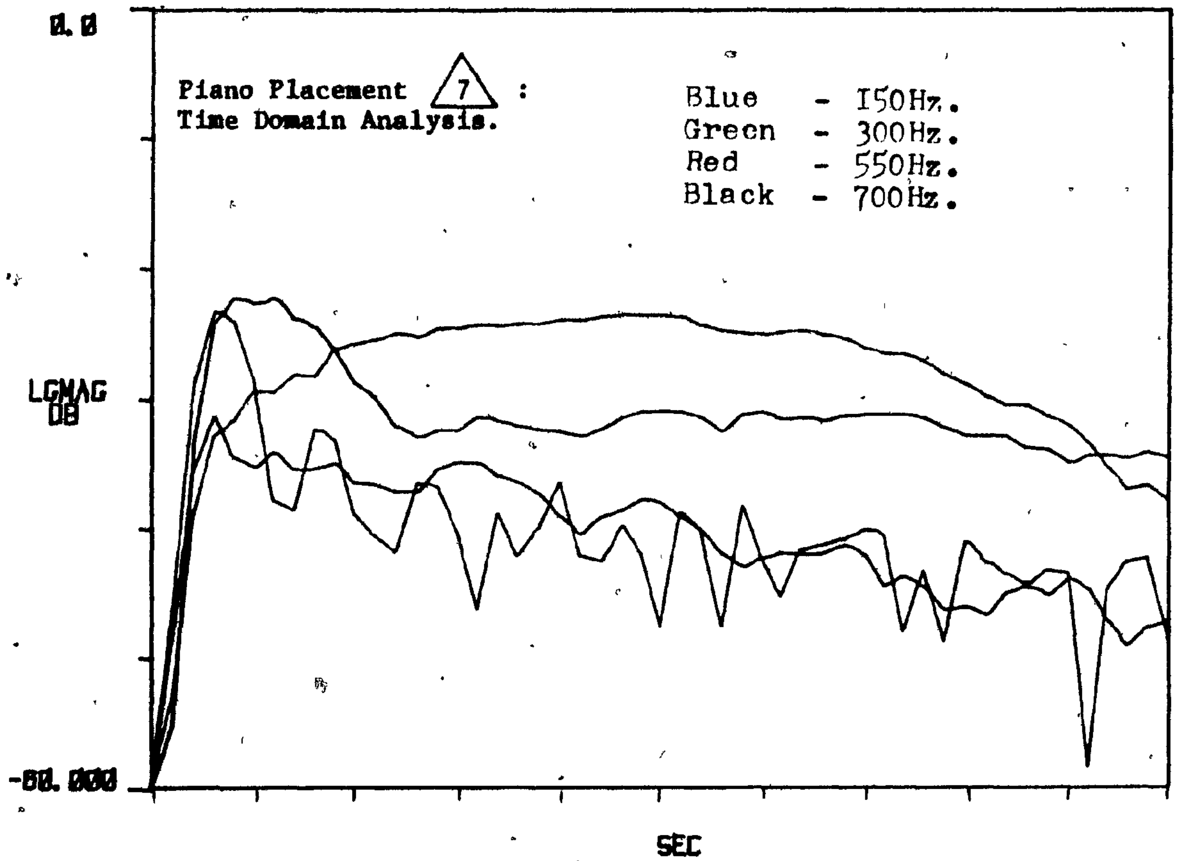

Piano Placement 6 :
Time Domain Analysis.
0.0
LGMAG
DB
-60.000
SEC
Red - 150Hz.
Blue - 300Hz.
Black - 550Hz.
Green - 700Hz.

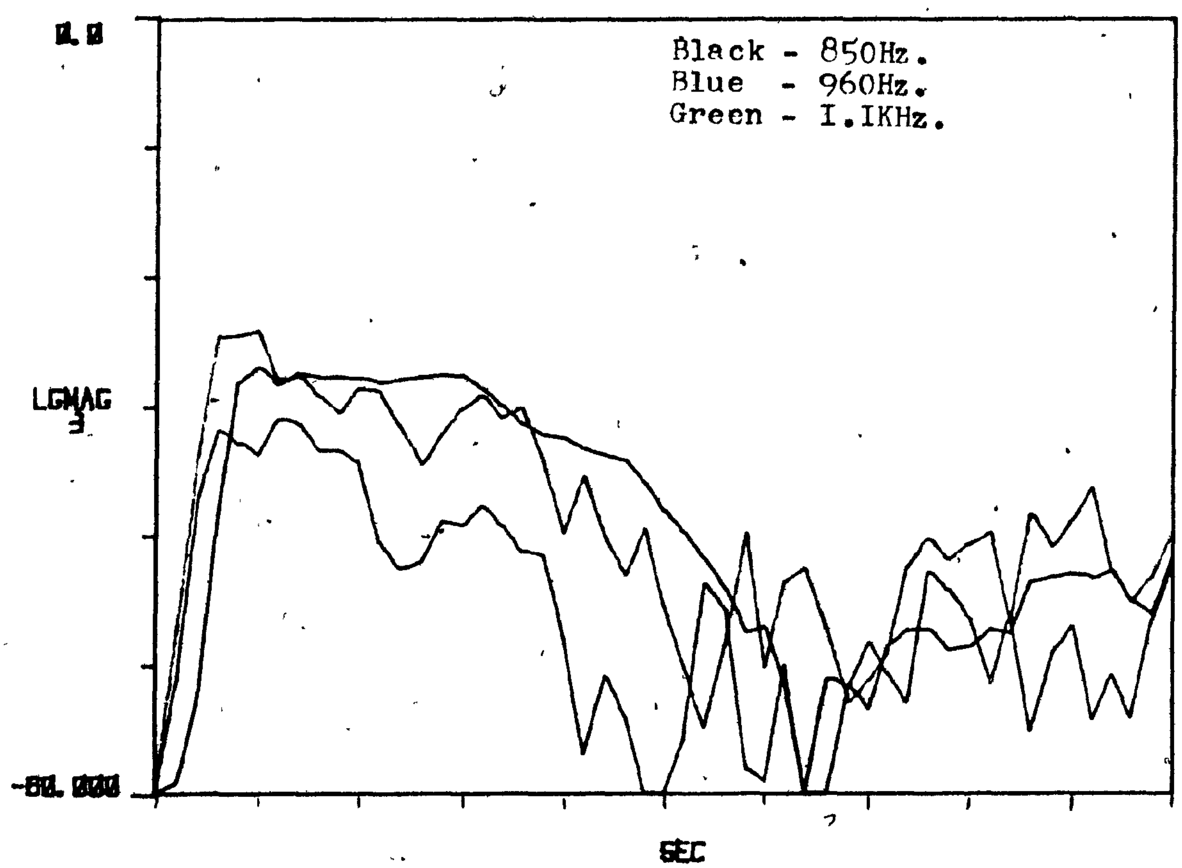

0.0
LGMAG
DB
-60.000
SEC
Green - 850Hz.
Red - 980Hz.
Blue - 1.1KHz.

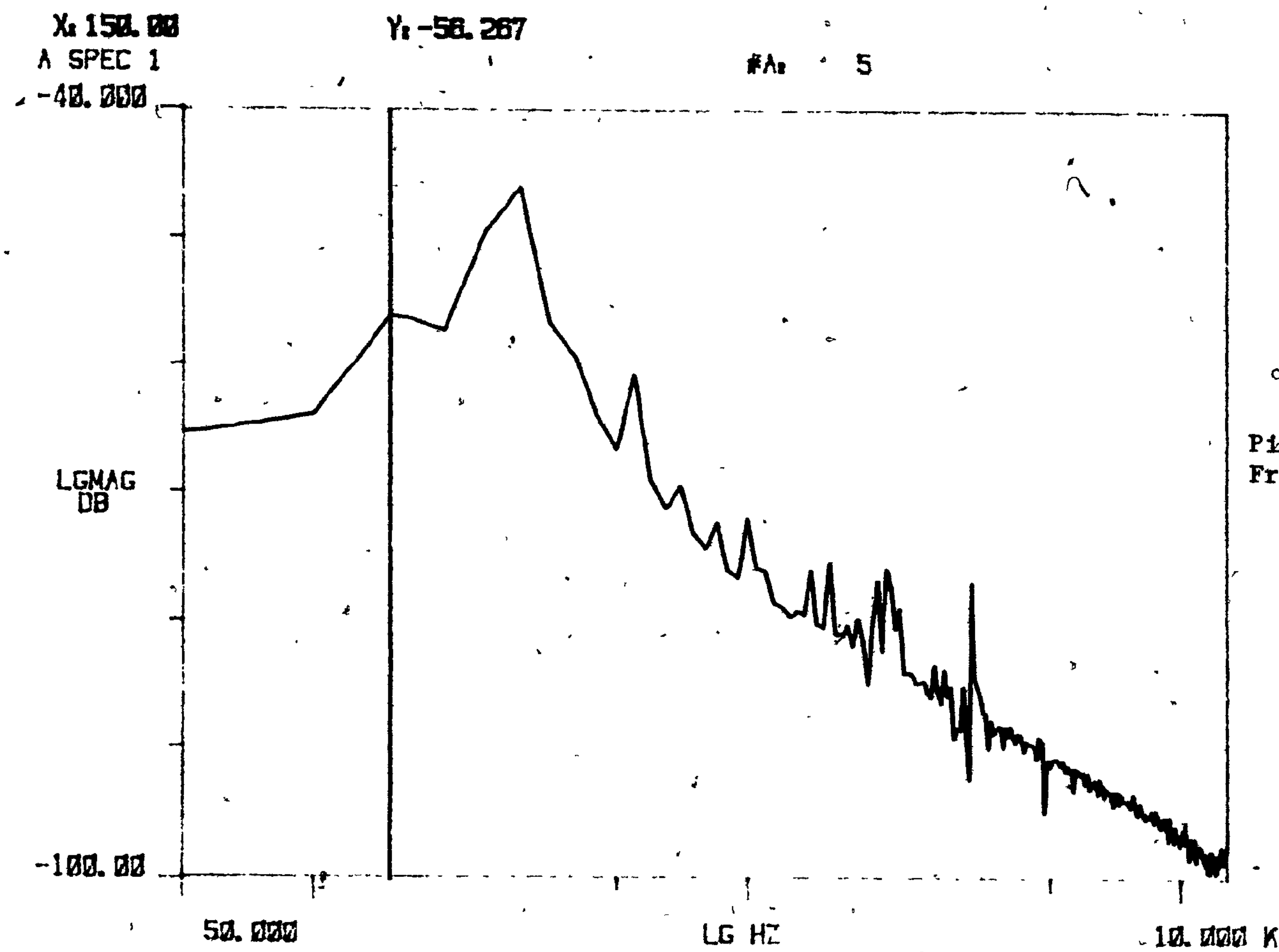


Piano Placement 7 : Frequency Domain Analysis.

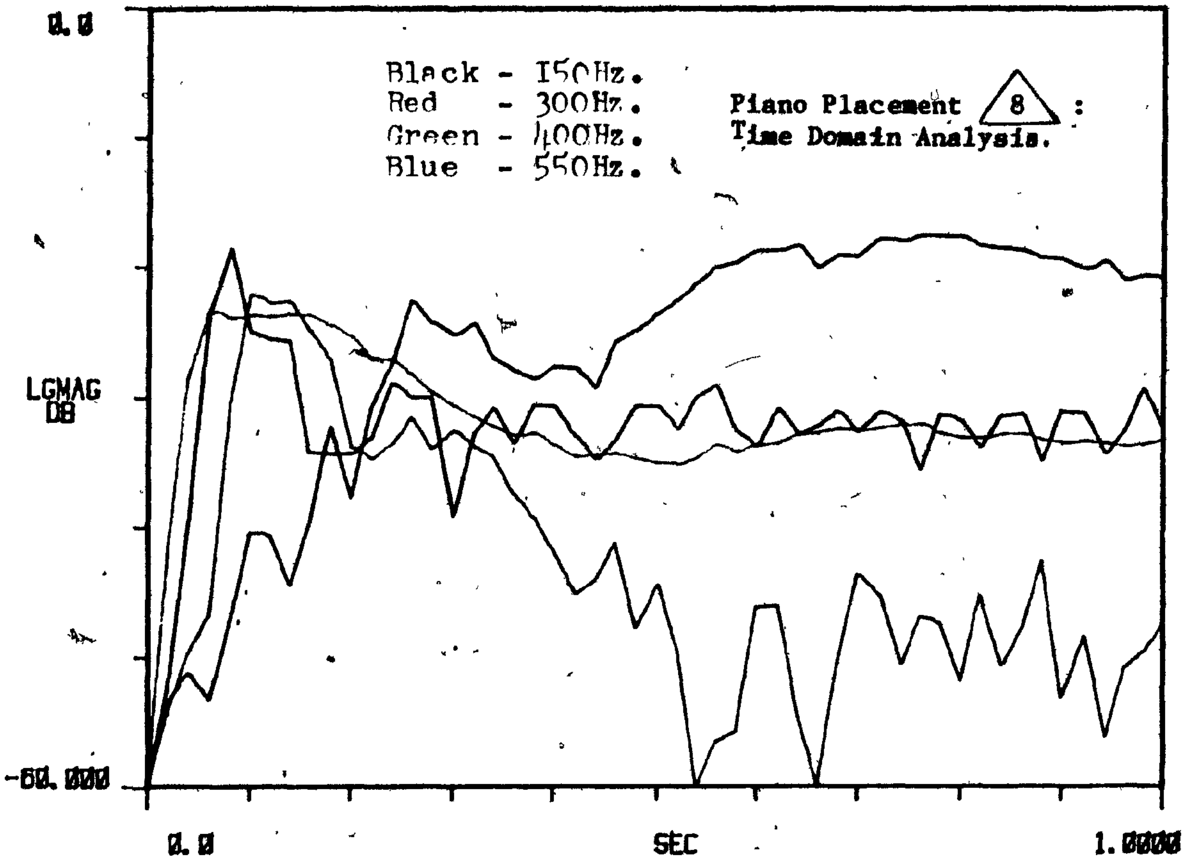
7

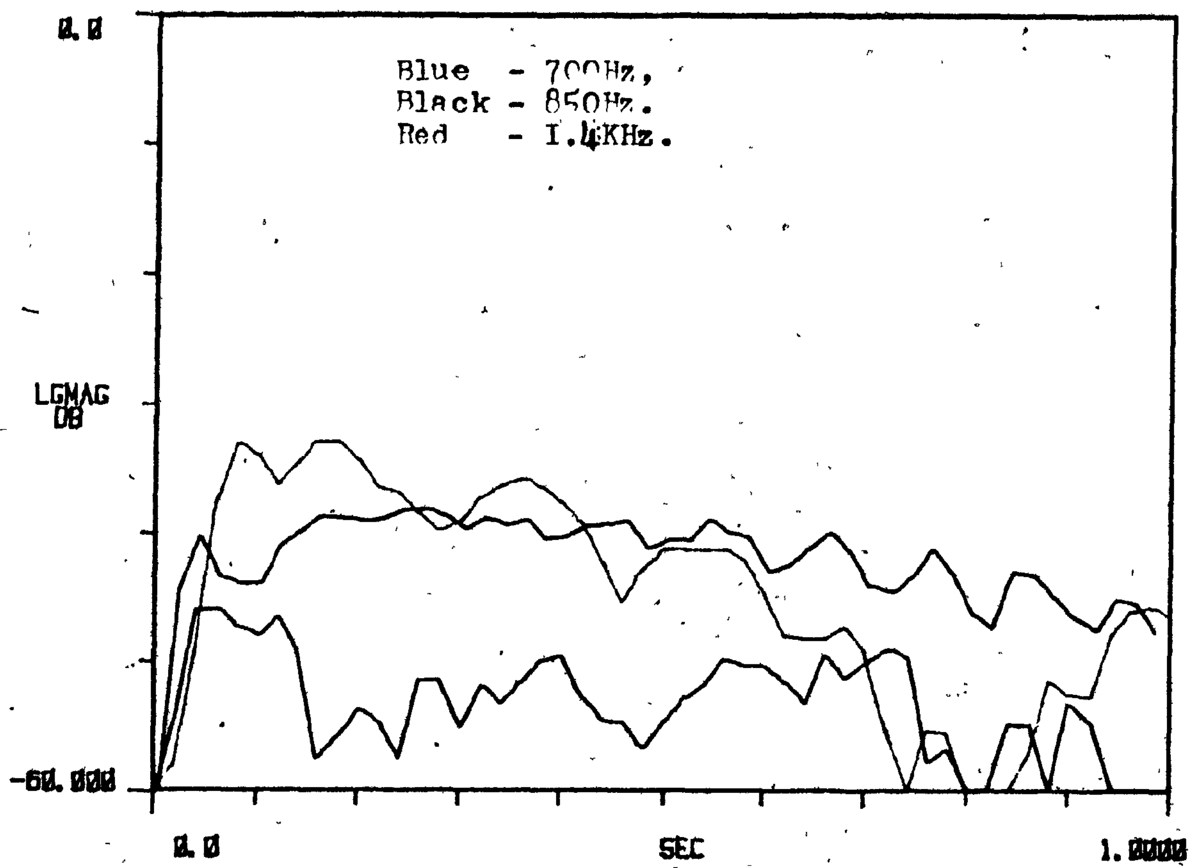

0.0
Piano Placement 7 :
Time Domain Analysis.
Blue - 150Hz.
Green - 300Hz.
Red - 550Hz.
Black - 700Hz.
LGMAG
DB
-80.000
SEC

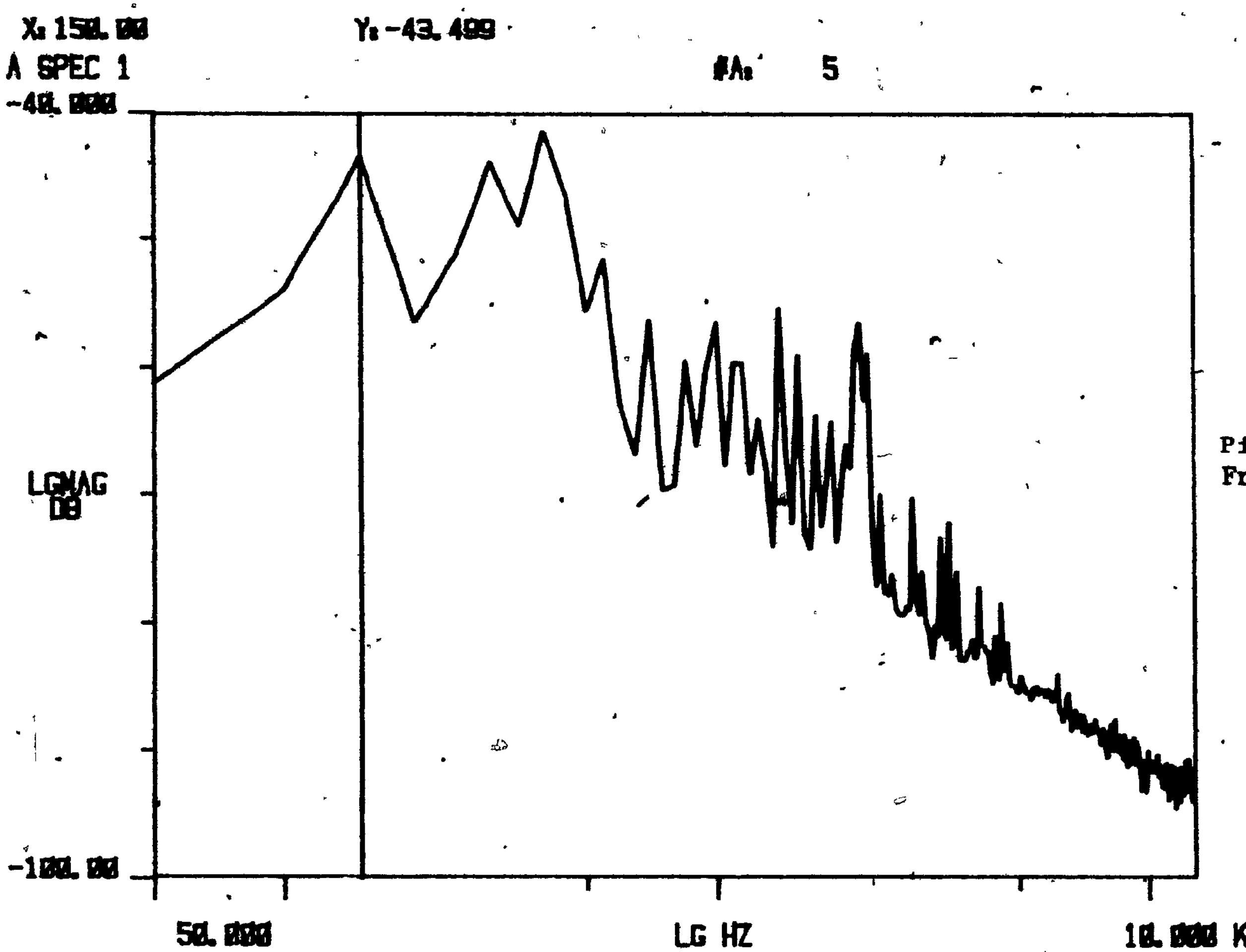

0.0
Black - 850Hz.
Blue - 960Hz.
Green - 1.1KHz.
LGMAG
-80.000
SEC



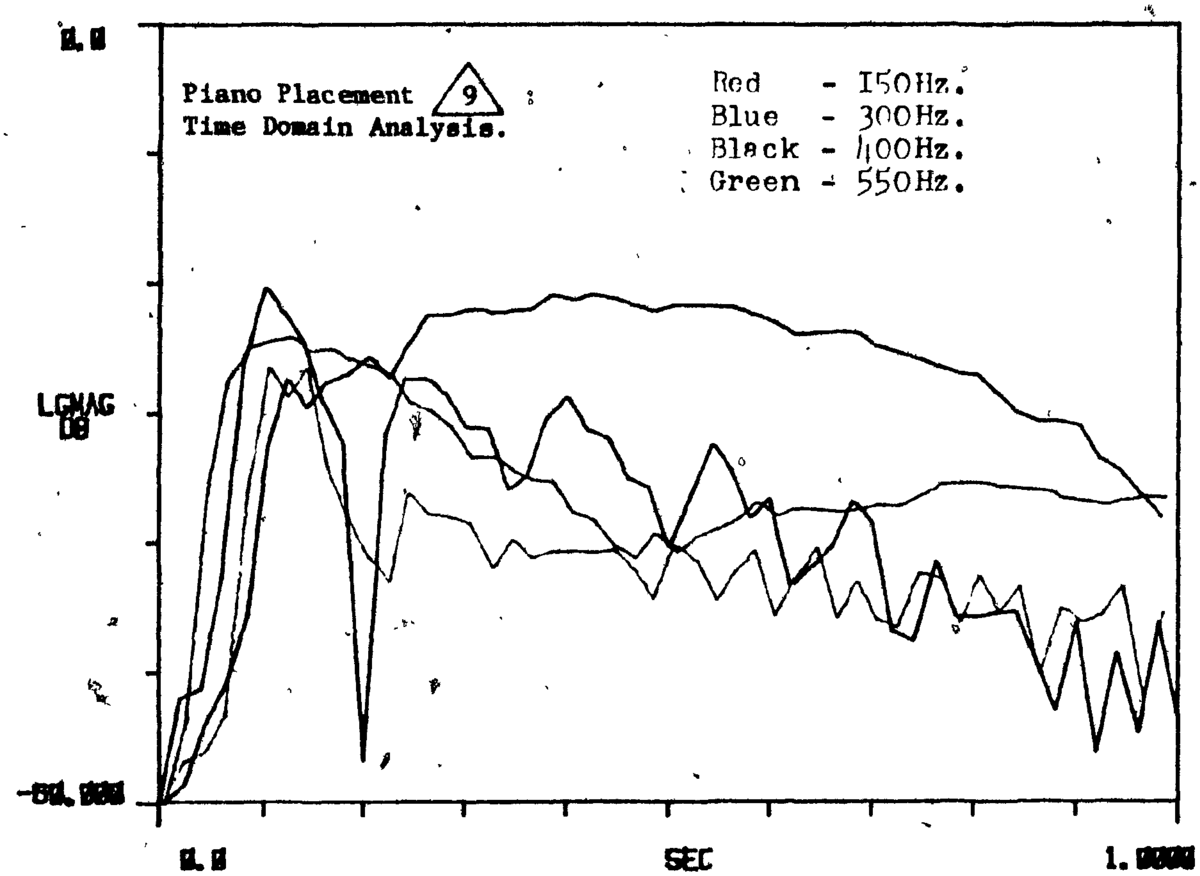
Piano Placement (8) :
Frequency Domain Analysis.

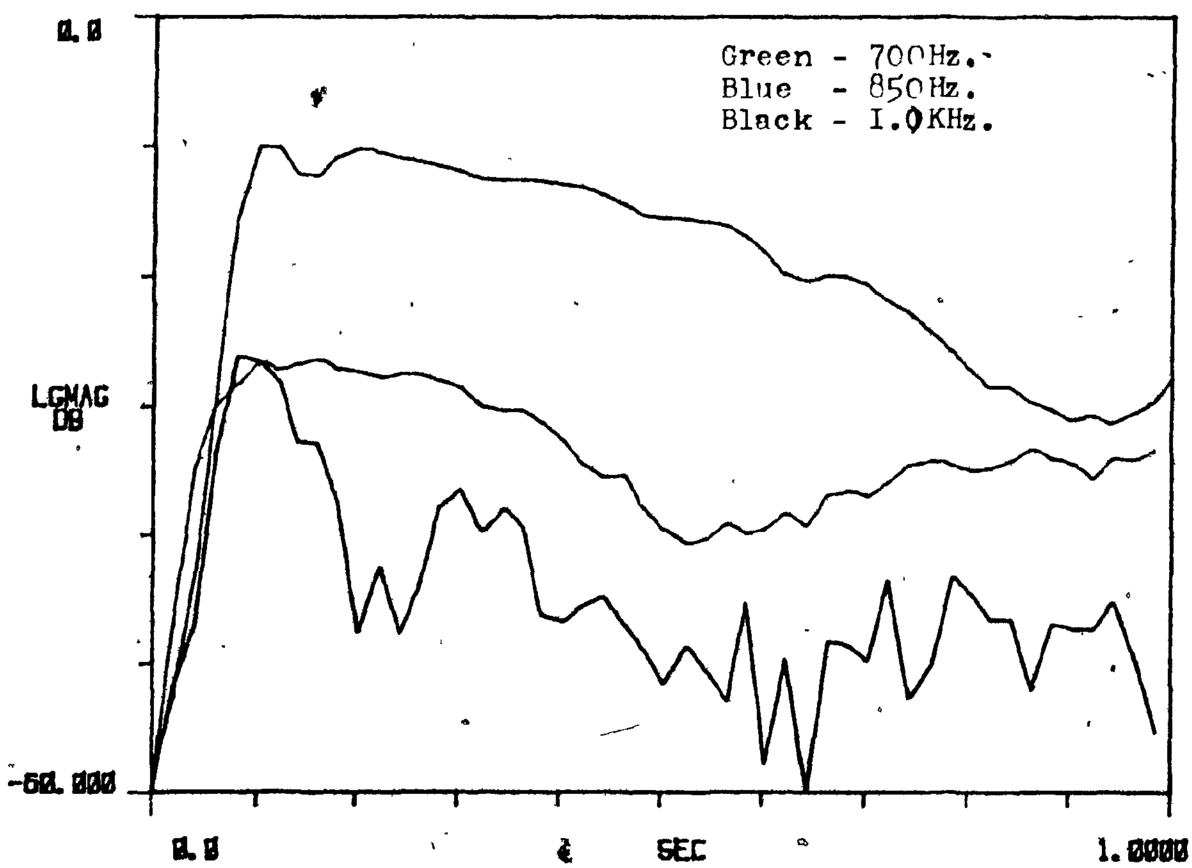

0.0
LGMAG DB
-60.000
0.0
SEC
1.0000
Black - 150Hz.
Red - 300Hz.
Green - 400Hz.
Blue - 550Hz.
Piano Placement 8 :
Time Domain Analysis.

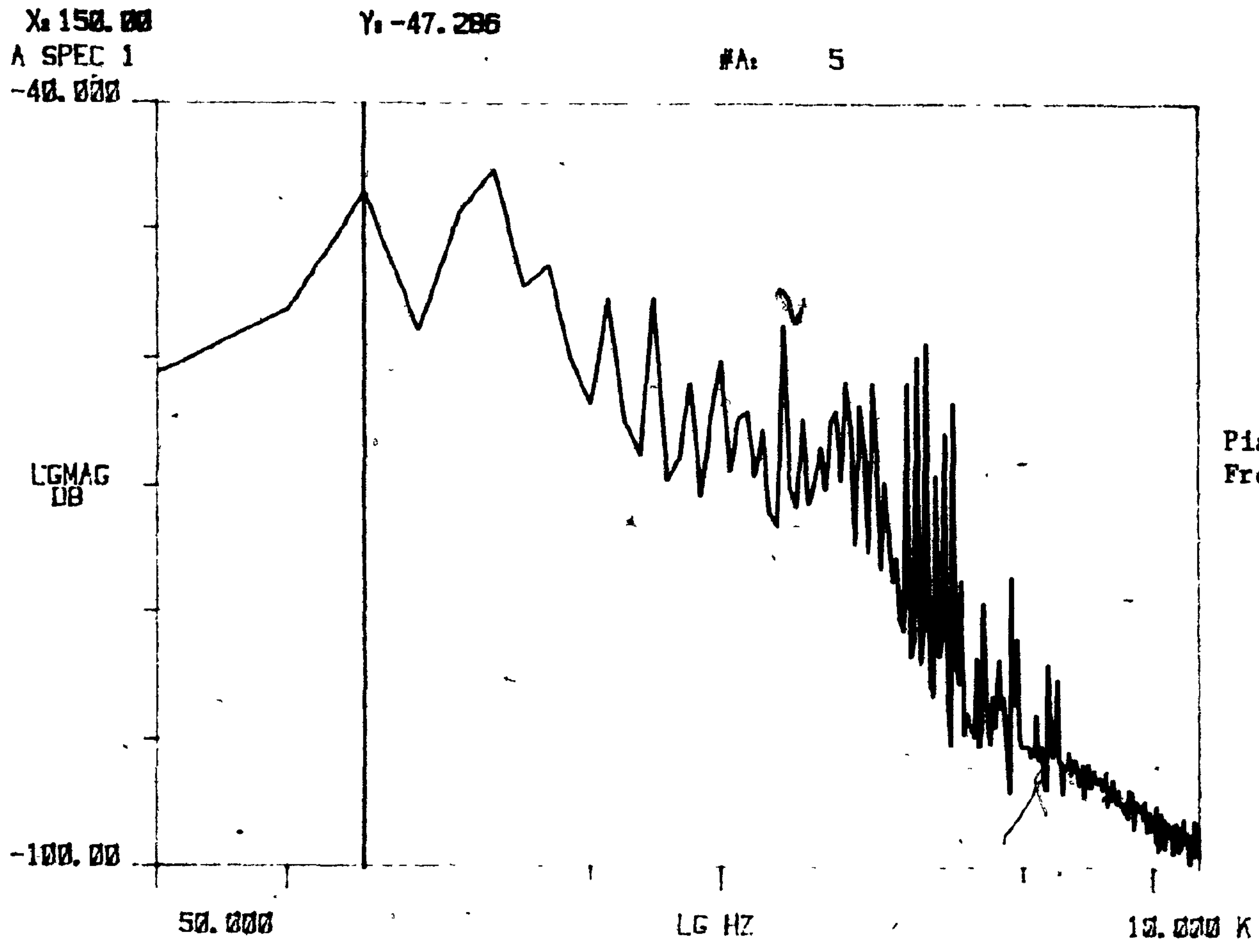

0.0
LGMAG DB
-60.000
0.0
SEC
1.0000
Blue - 700Hz,
Black - 850Hz.
Red - 1.4KHz.



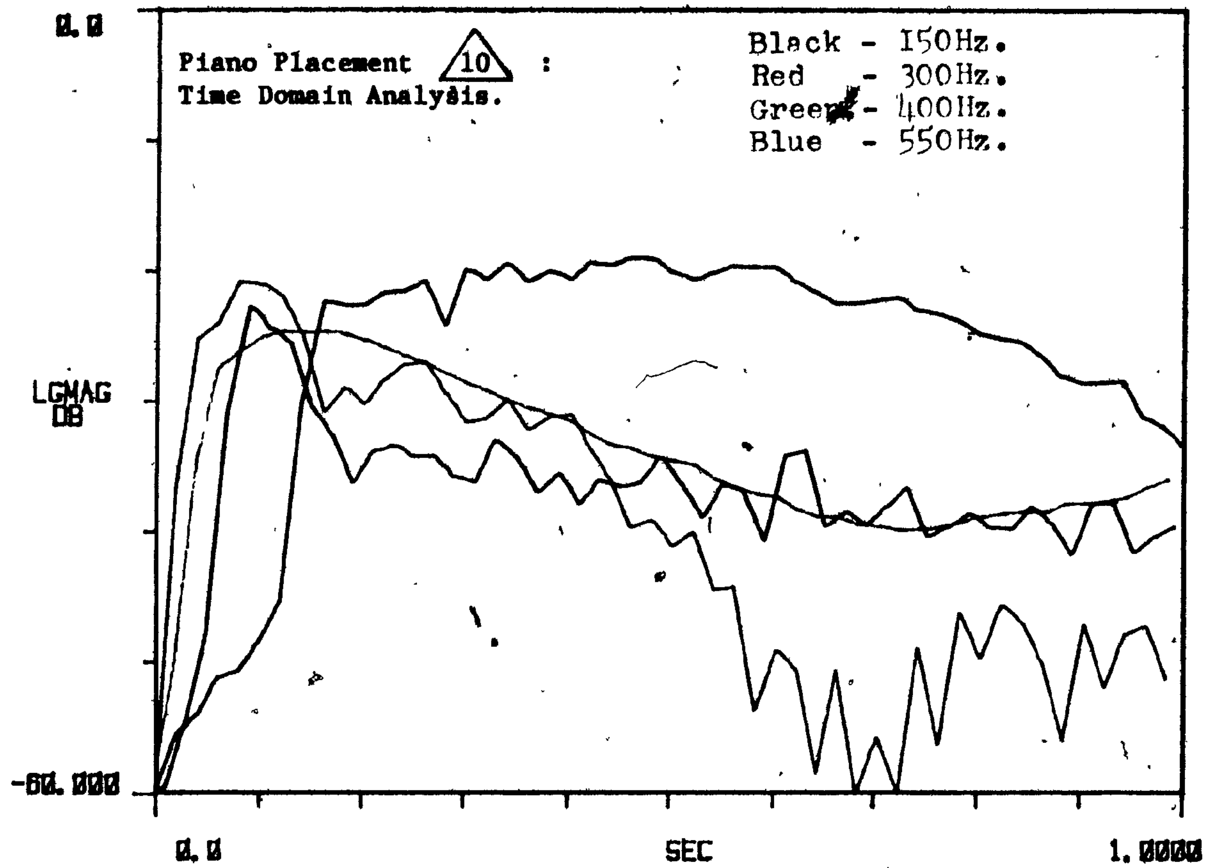
Piano Placement (9): Frequency Domain Analysis.


Piano Placement 9 :
Time Domain Analysis.
Red - 150Hz.
Blue - 300Hz.
Black - 400Hz.
Green - 550Hz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000

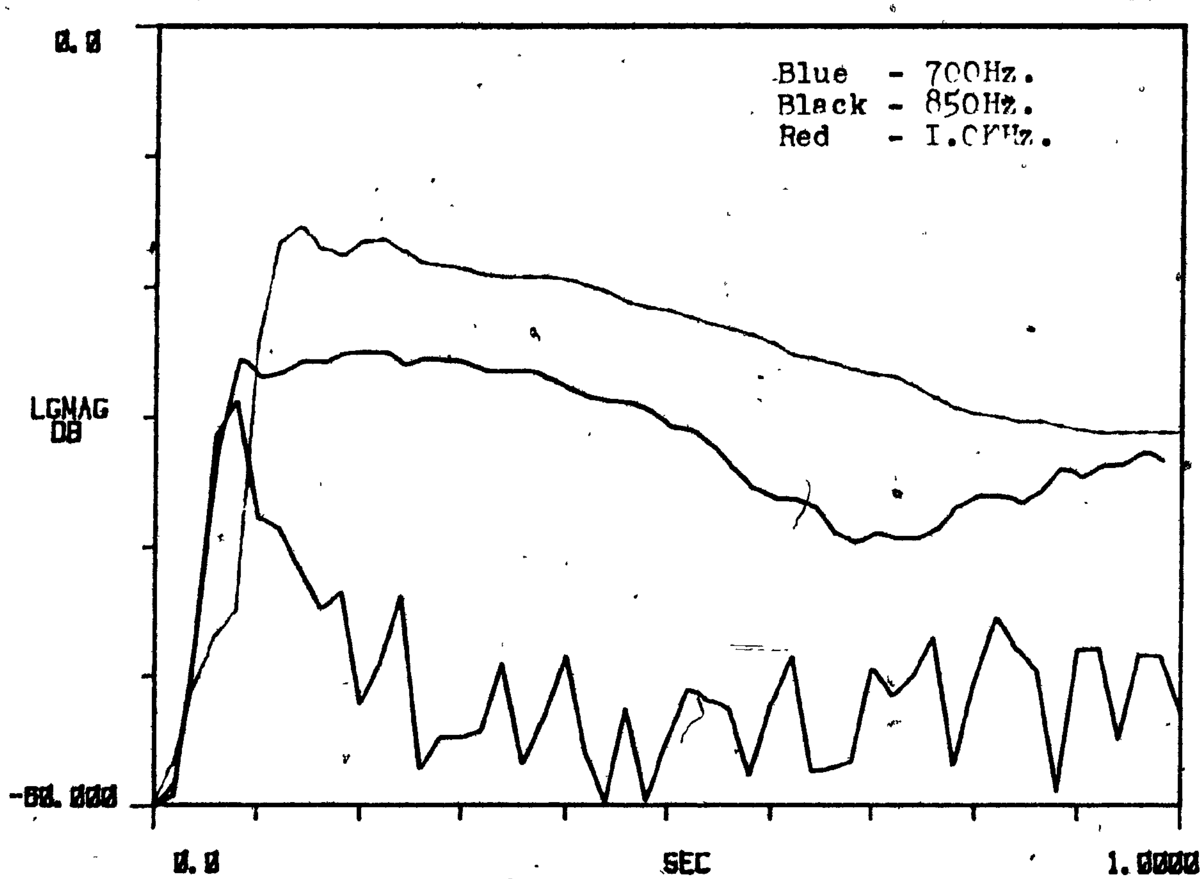

Green - 700Hz.
Blue - 850Hz.
Black - 1.0KHz.
0.0
LGMAG
DB
-60.000
0.0
SEC
1.0000



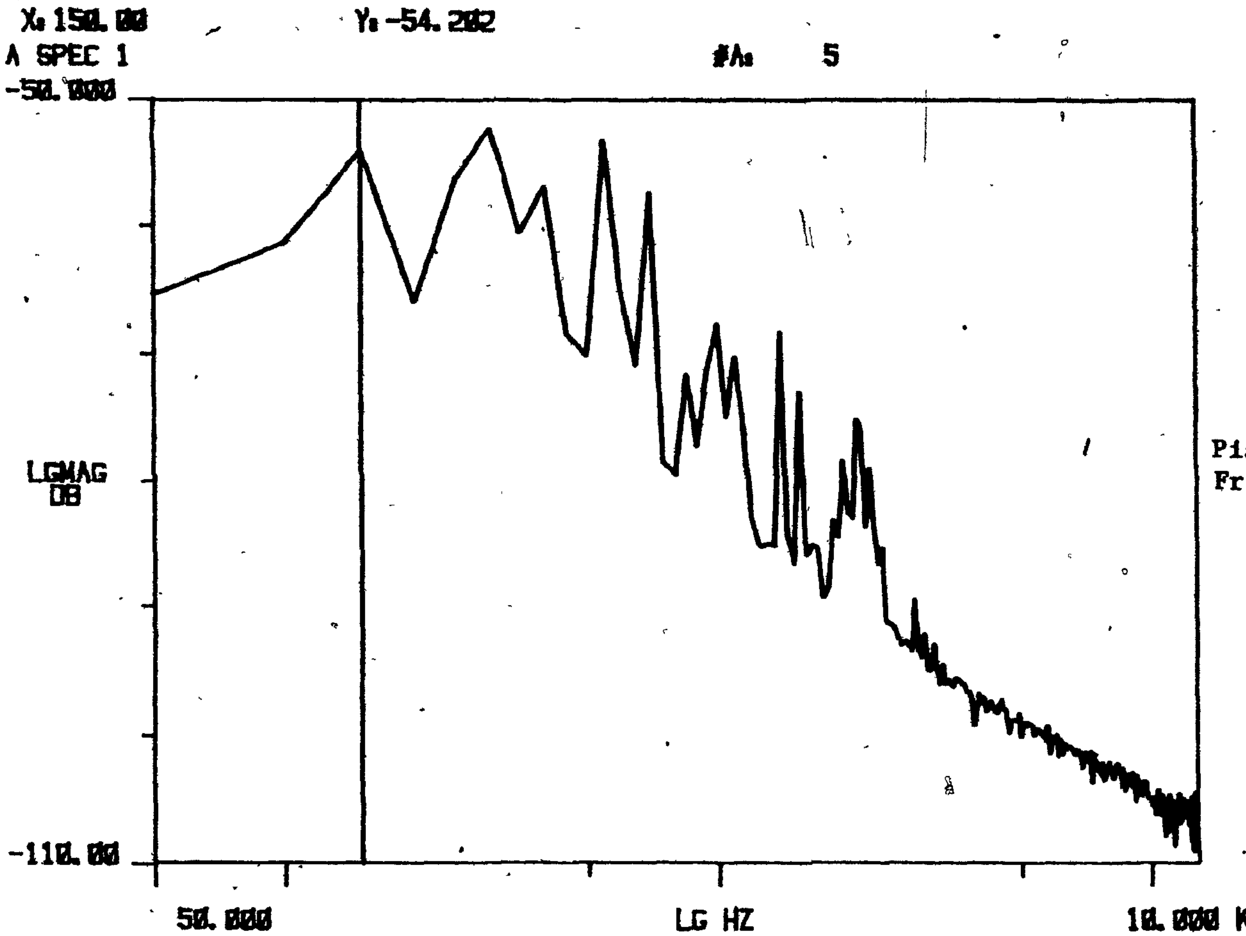
Piano Placement (10) :
Frequency Domain Analysis.



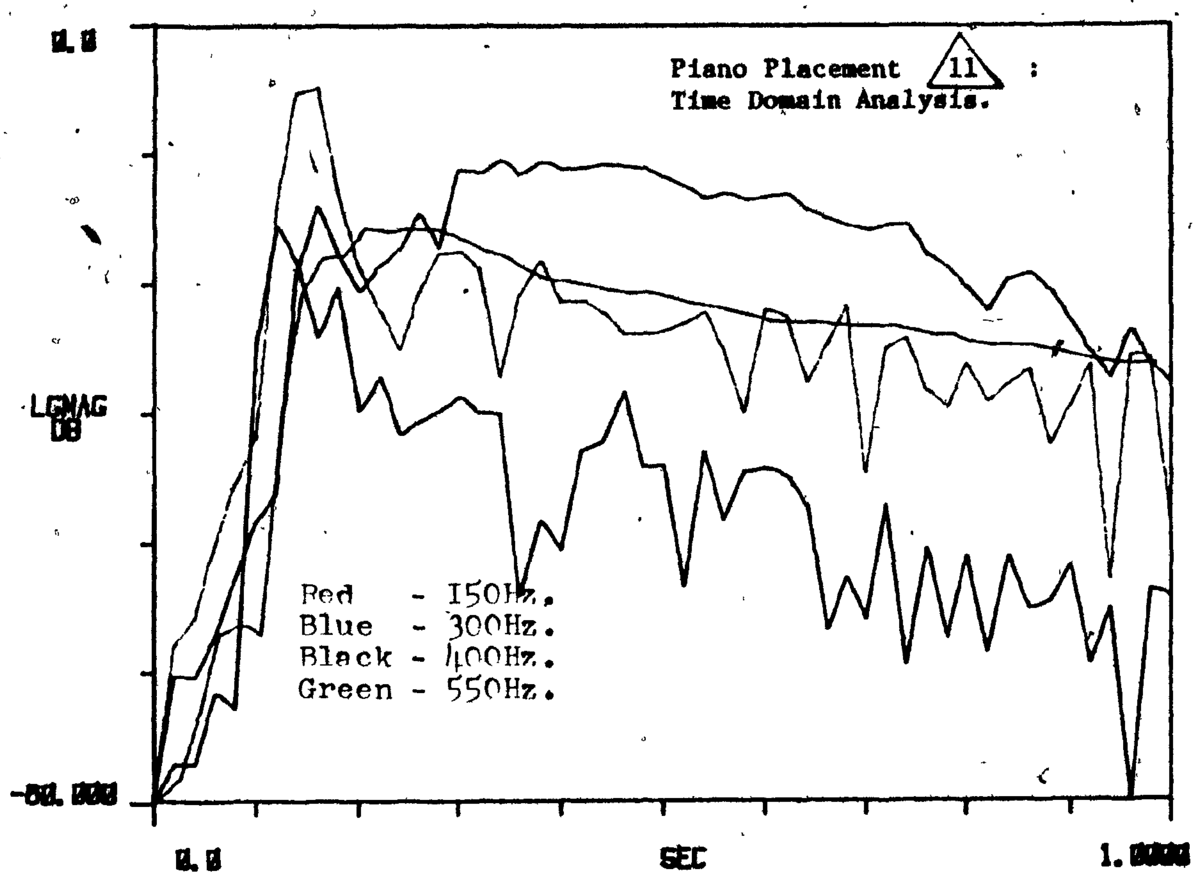
0.0
Piano Placement 10 :
Time Domain Analysis.
Black - 150Hz.
Red - 300Hz.
Green - 400Hz.
Blue - 550Hz.
LGMAG
DB
-60.000
0.0
SEC
1.0000

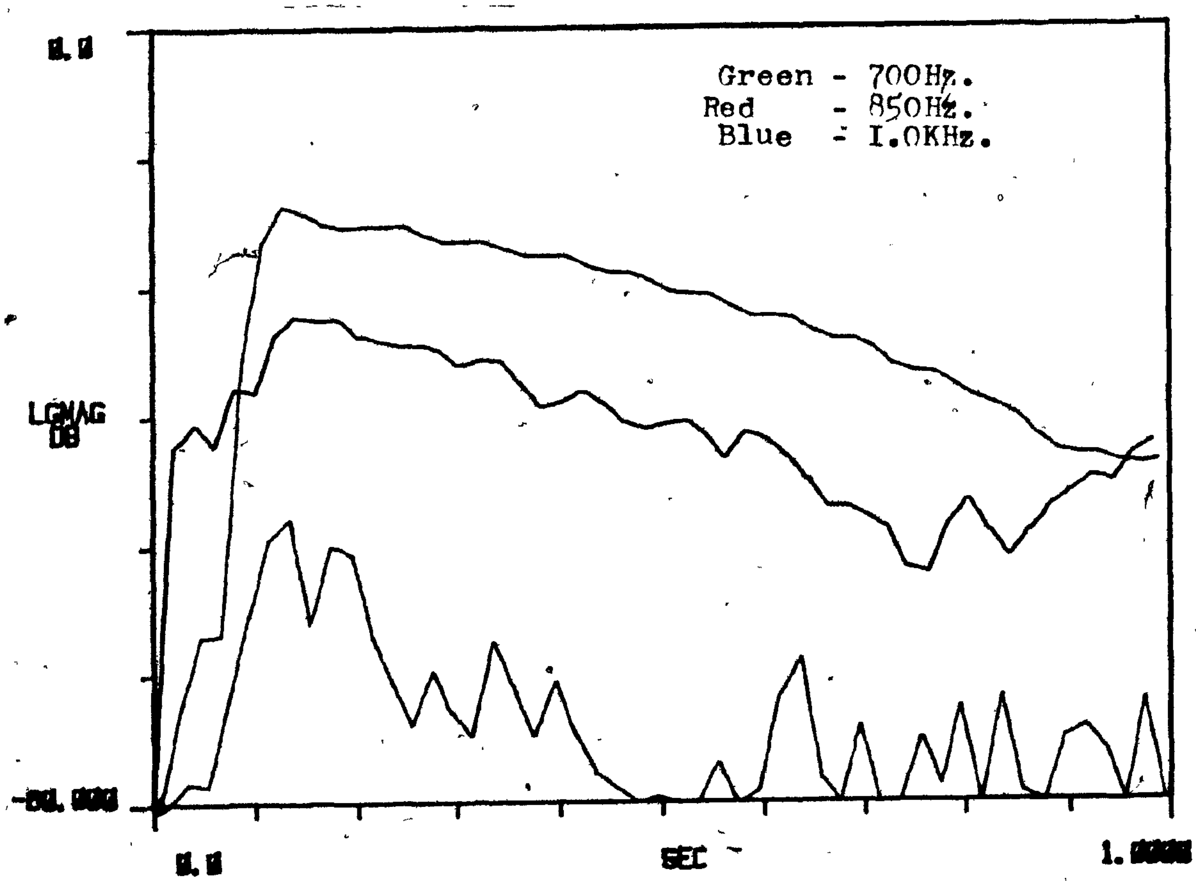


0.0
Blue - 700Hz.
Black - 850Hz.
Red - 1.0KHz.
LGMAG
DB
-60.000
0.0
SEC
1.0000



Piano Placement (11) : Frequency Domain Analysis.


Piano Placement 11 :
Time Domain Analysis.
0.0
LGMAG
DB
-80.000
0.0
SEC
1.0000
Red - 150Hz.
Blue - 300Hz.
Black - 400Hz.
Green - 550Hz.

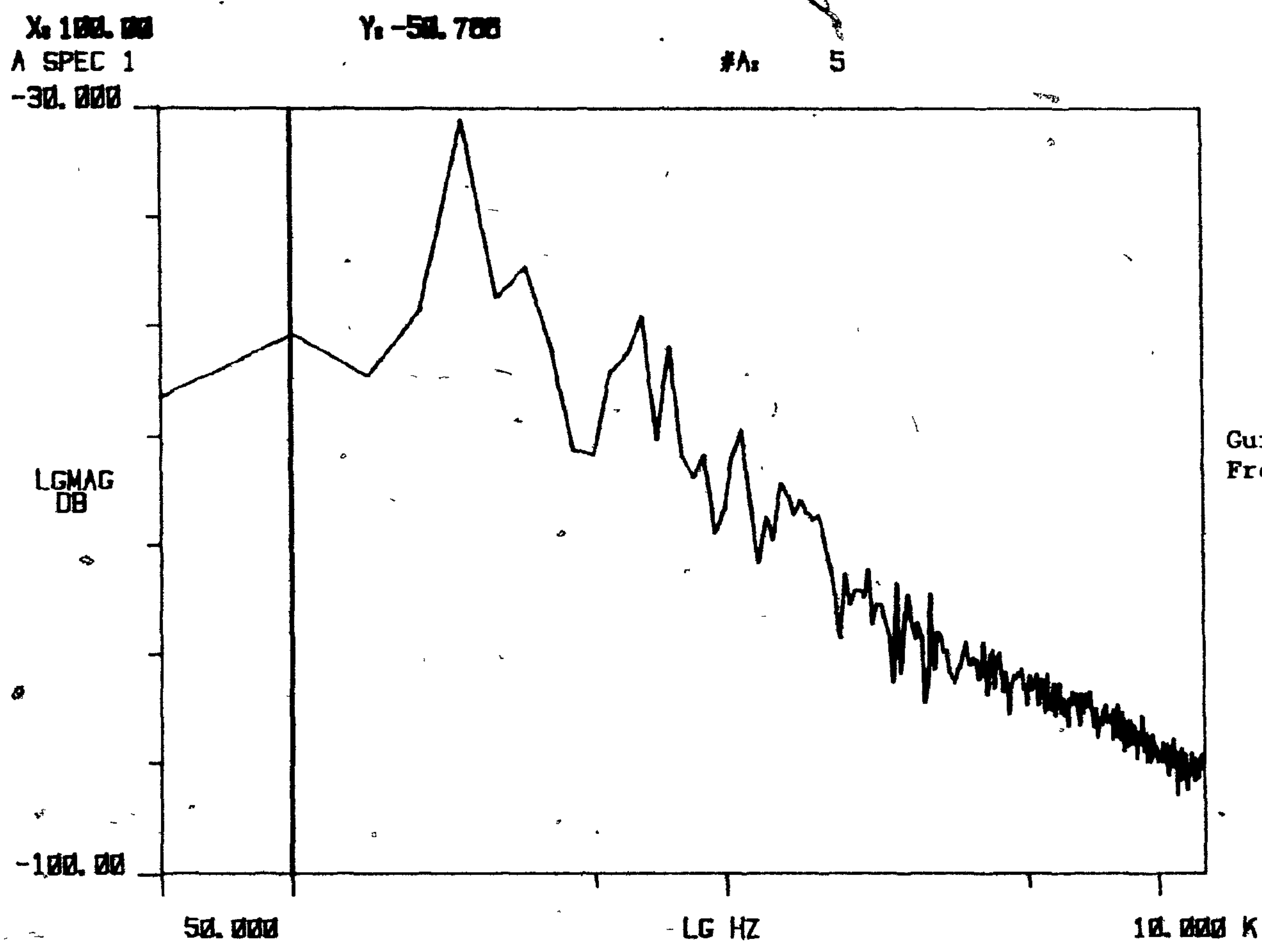

0.0
Green - 700Hz.
Red - 850Hz.
Blue - 1.0KHz.
LGMAG
DB
-80.000
0.0
SEC
1.0000

APPENDIX VI

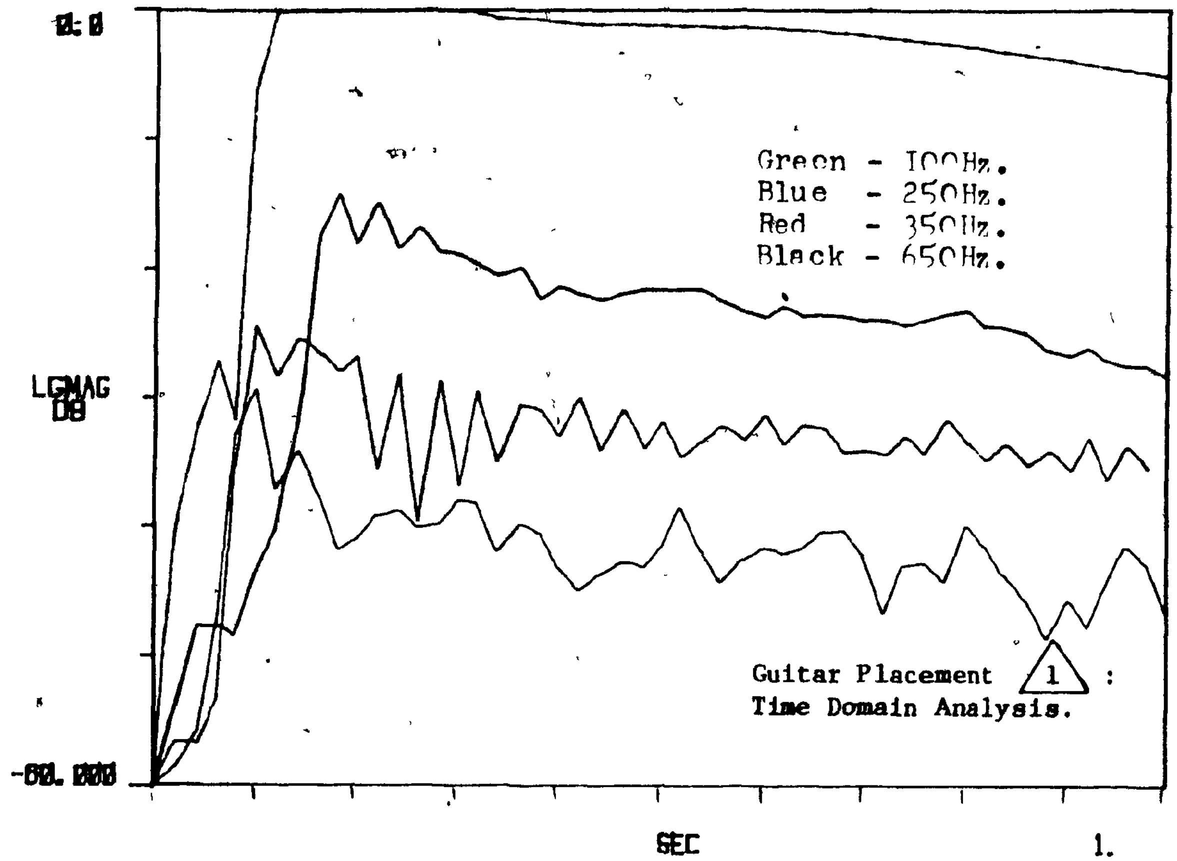
Guitar

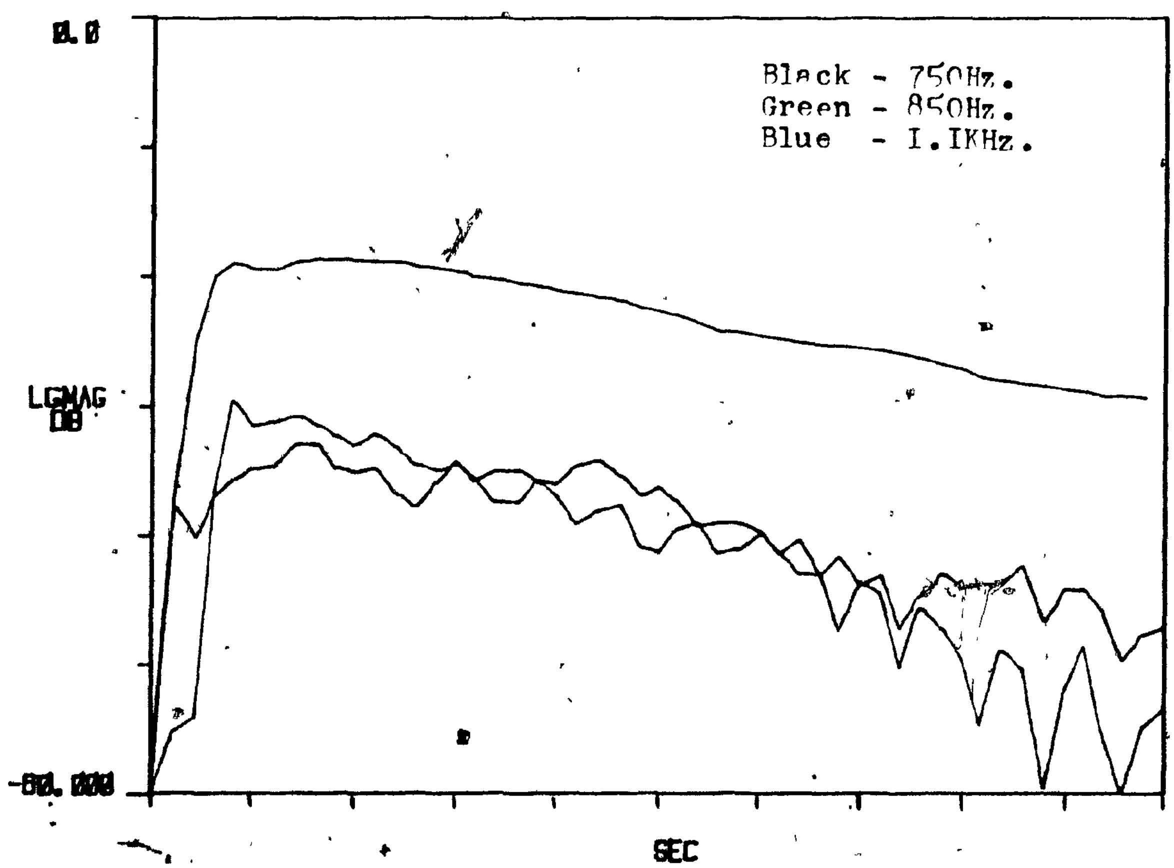
Spectrum Analysis

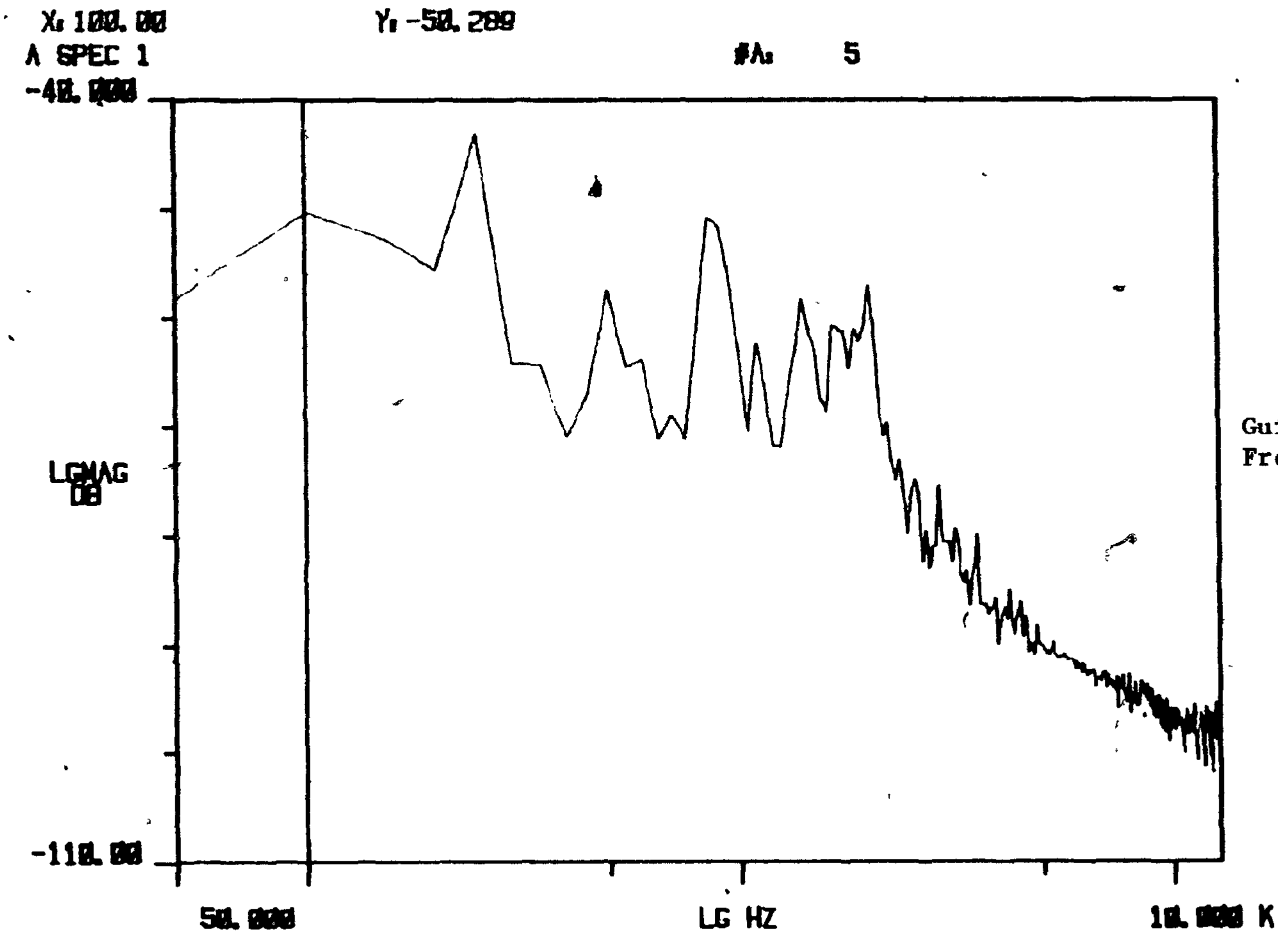
211



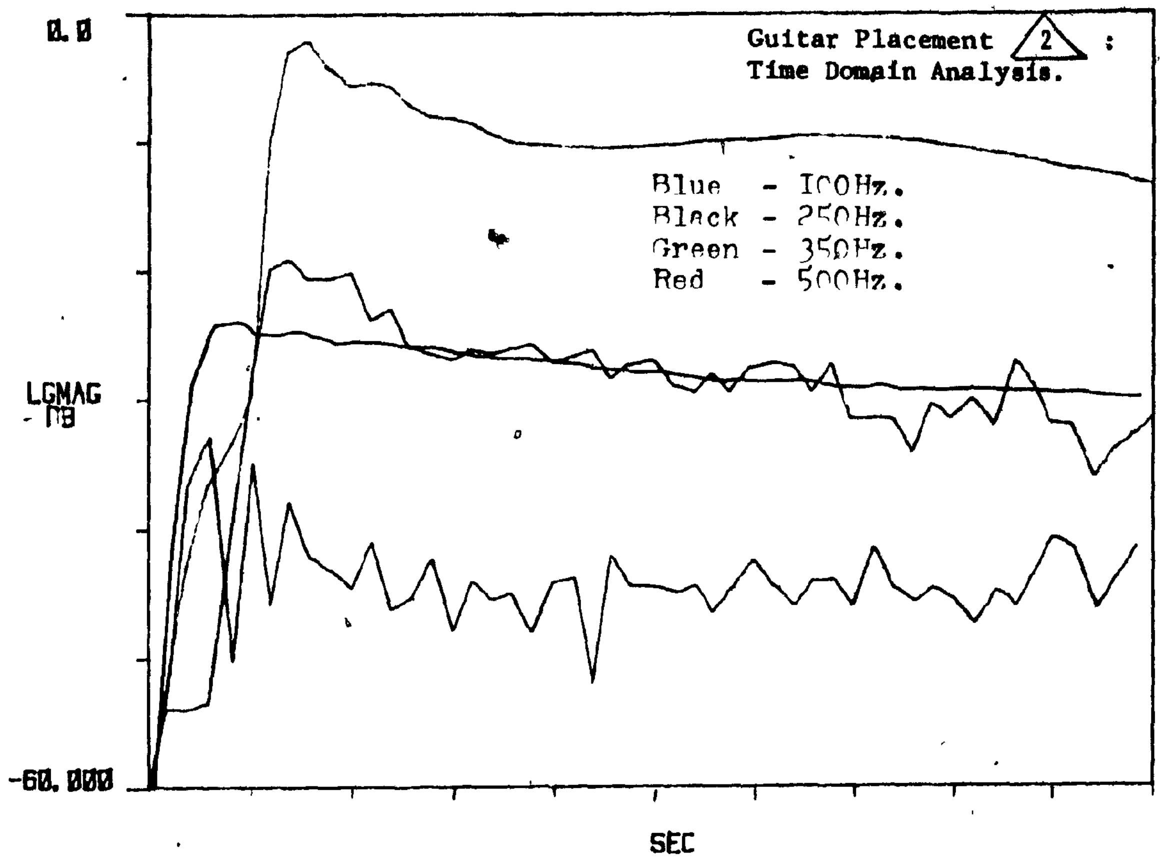
Guitar Placement (1) :
Frequency Domain Analysis.

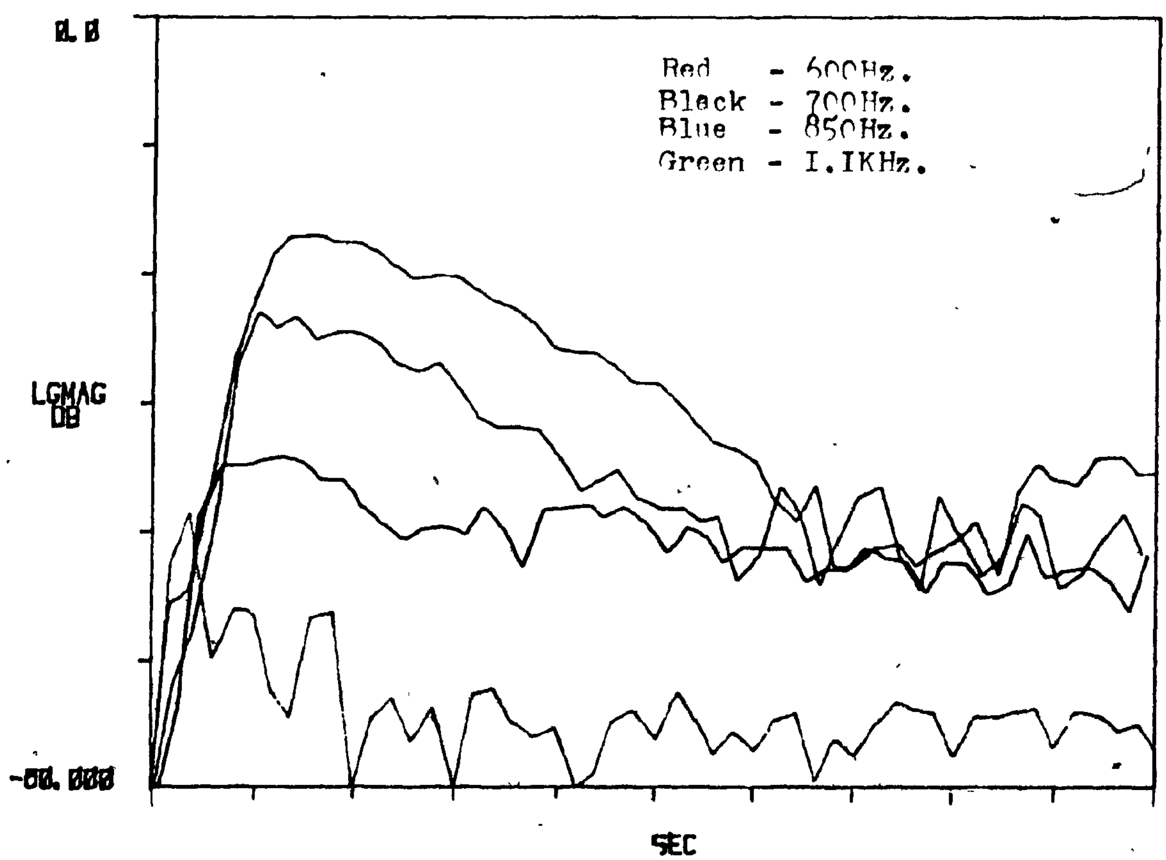

0.0
LGMAG DB
-80.000
SEC
1.
Green - 100Hz.
Blue - 250Hz.
Red - 350Hz.
Black - 650Hz.
Guitar Placement 1 :
Time Domain Analysis.


0.0
LGMAG DB
-80.000
SEC
Black - 750Hz.
Green - 850Hz.
Blue - 1.1KHz.

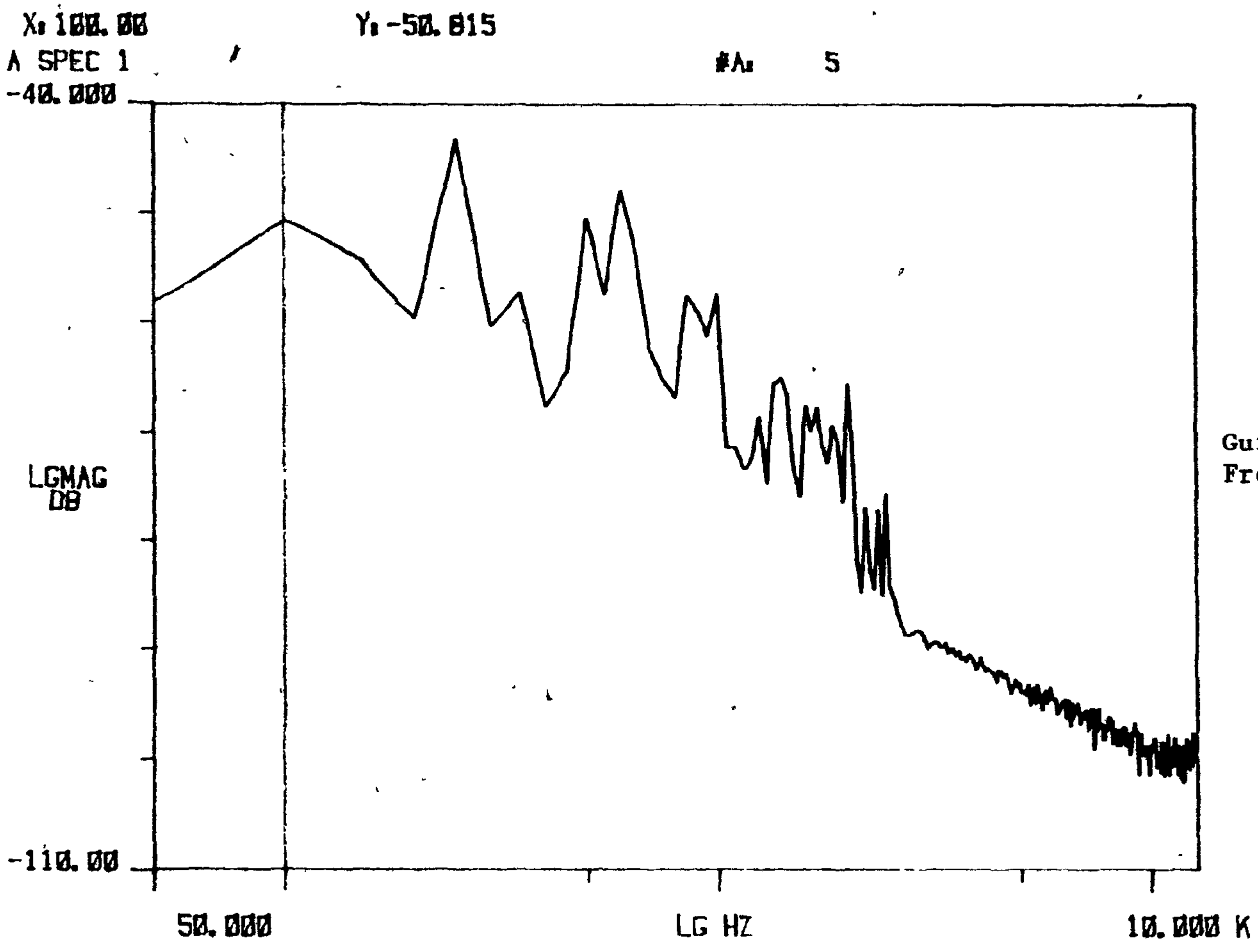


Guitar Placement (2) :
Frequency Domain Analysis.

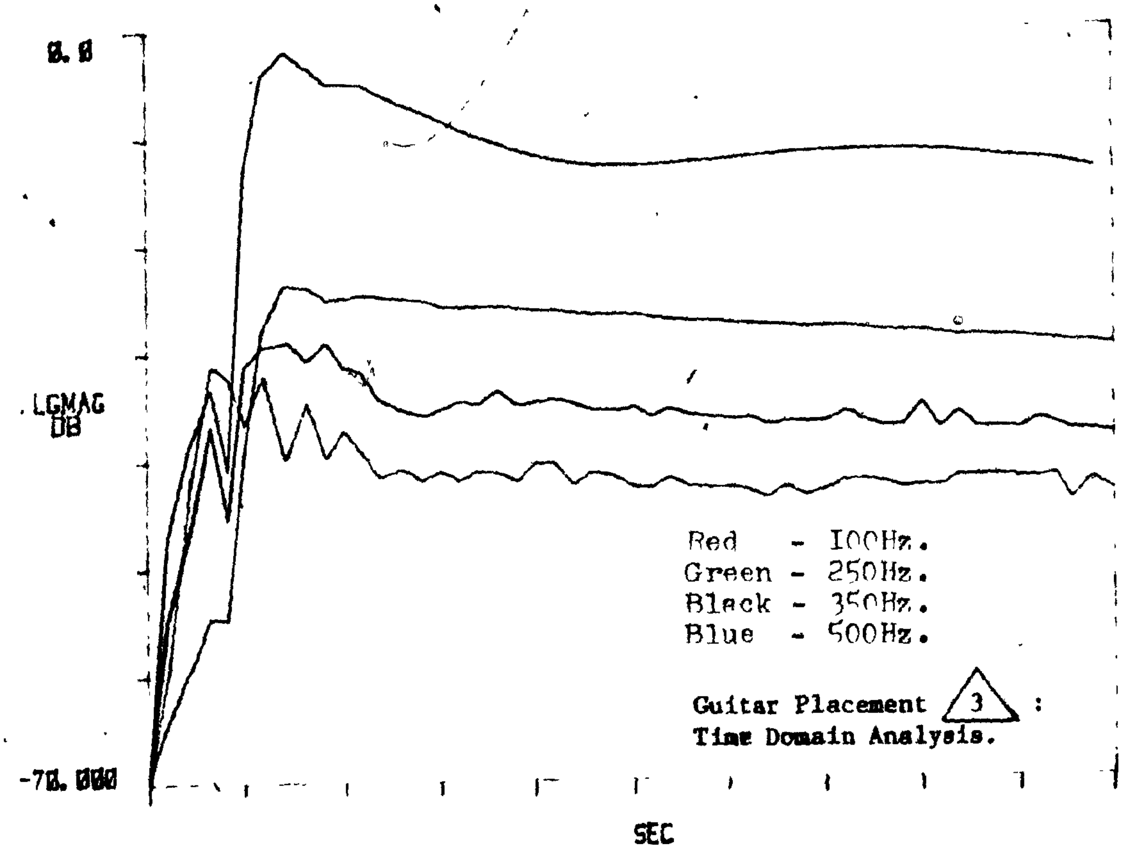

Guitar Placement 2 :
Time Domain Analysis.
Blue - 100Hz.
Black - 250Hz.
Green - 350Hz.
Red - 500Hz.
0.0
LGMAG
DB
-60.000
SEC

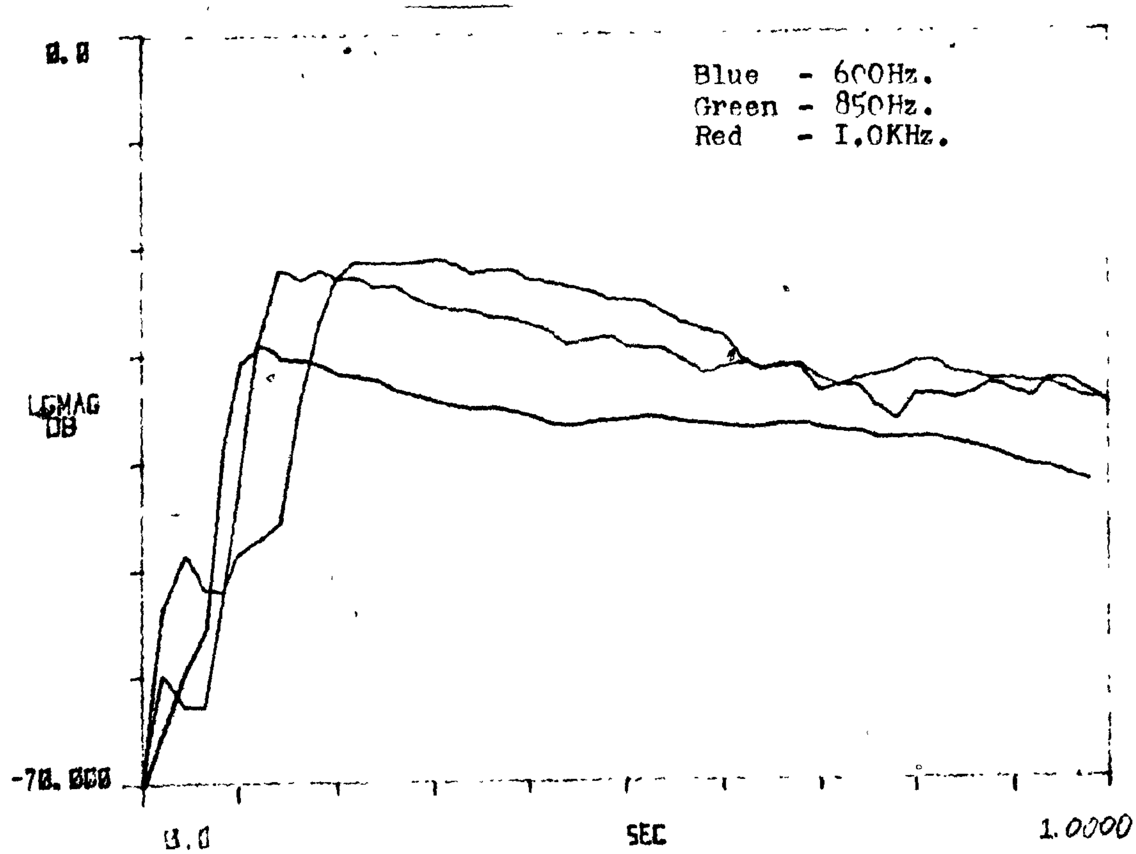

Red - 600Hz.
Black - 700Hz.
Blue - 850Hz.
Green - 1.1KHz.
0.0
LGMAG
DB
-60.000
SEC

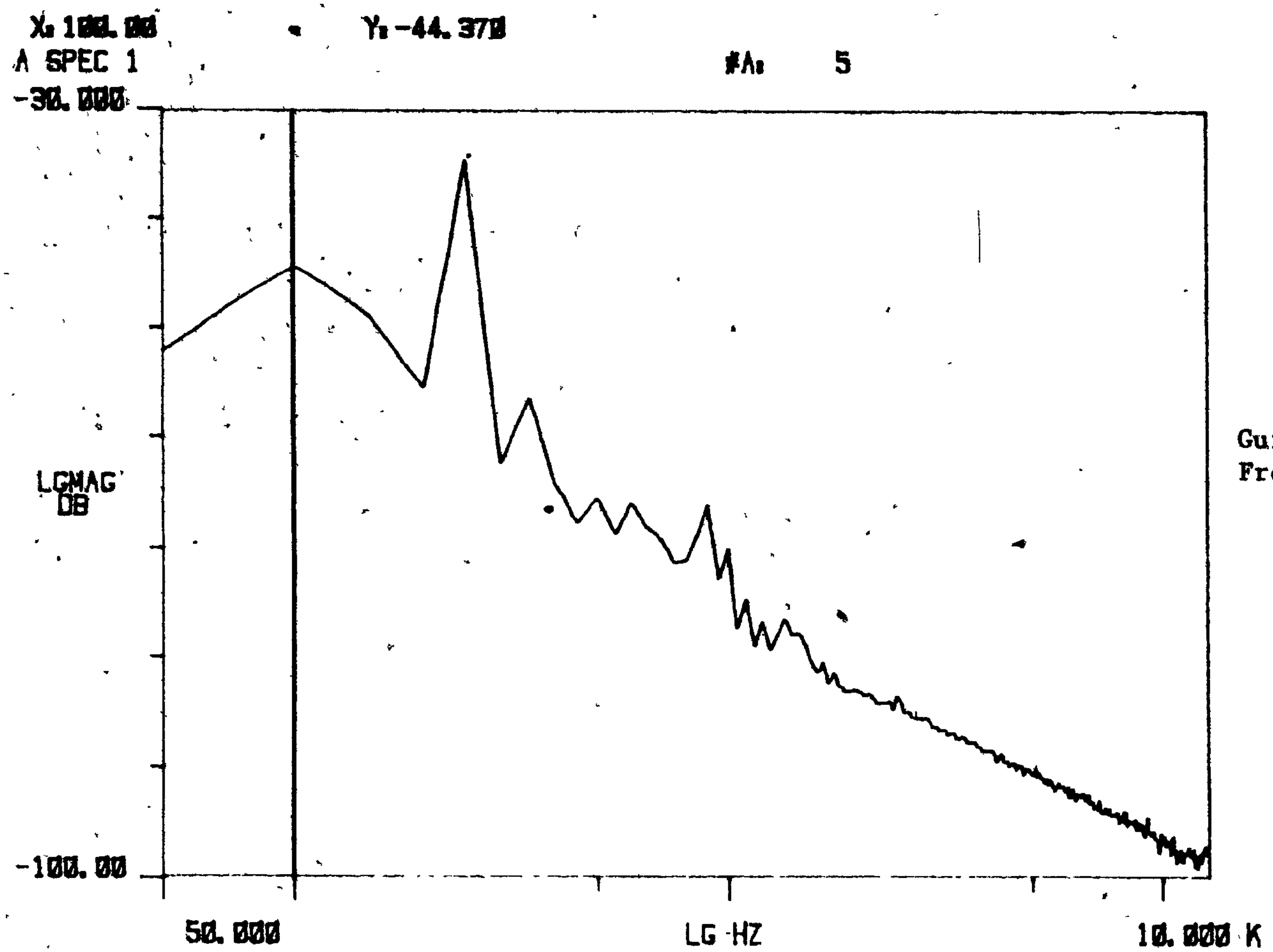
2/5



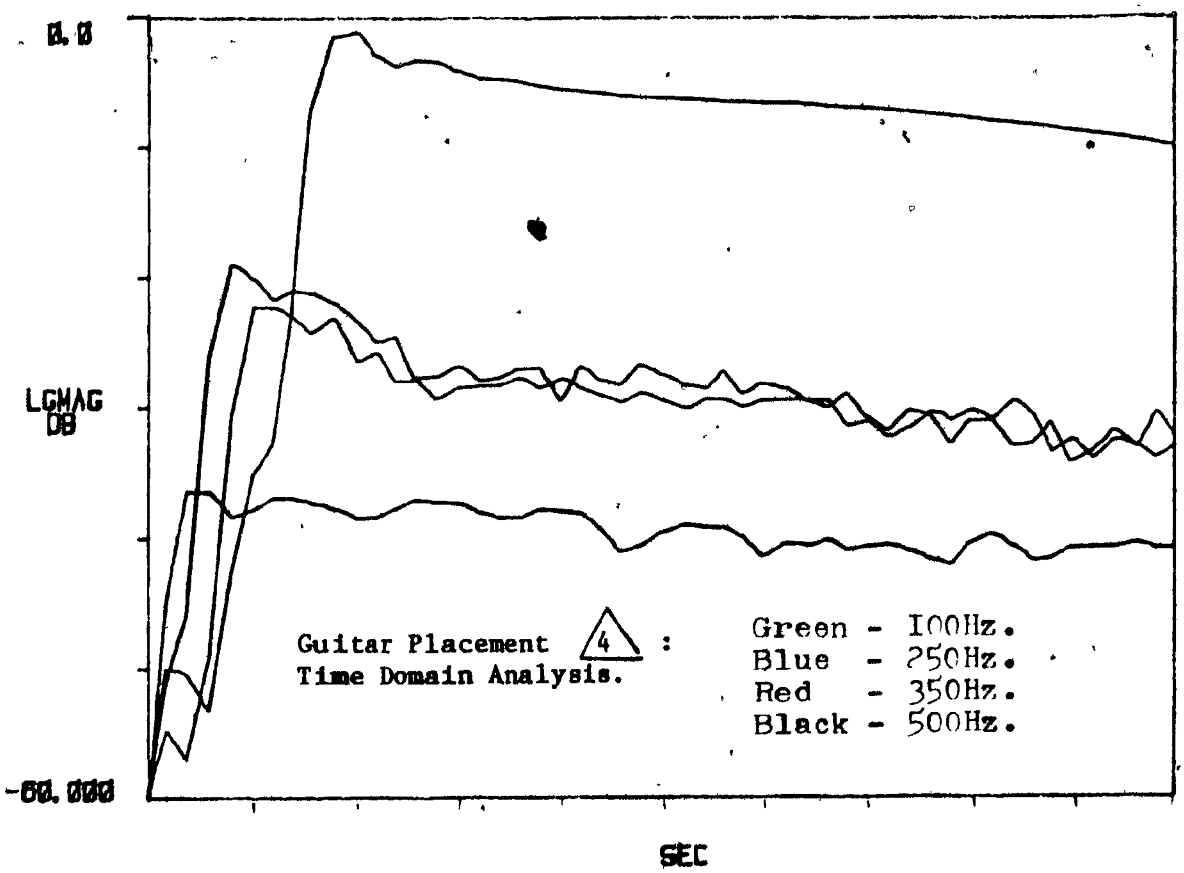
Guitar Placement (3): Frequency Domain Analysis.

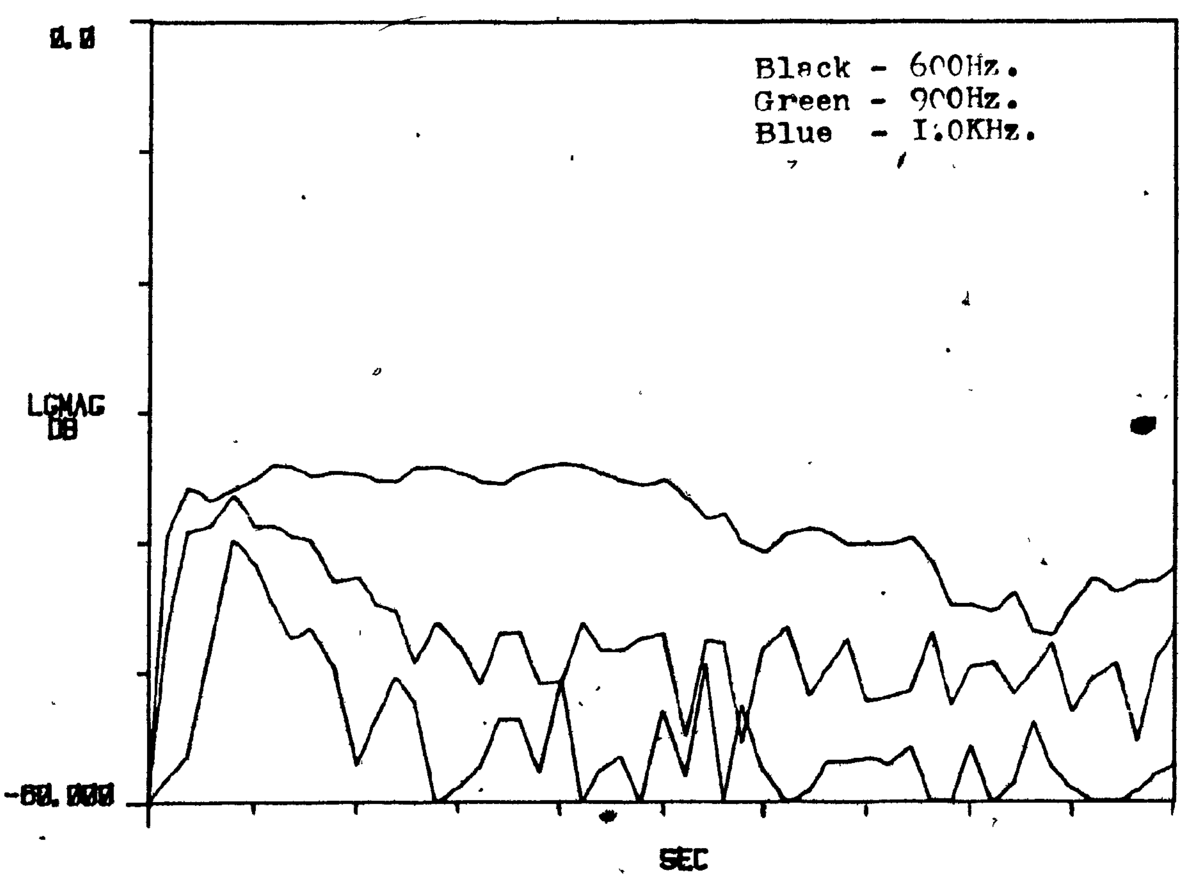

0.0
LGMAG
DB
-70.000
SEC
Red - 100Hz.
Green - 250Hz.
Black - 350Hz.
Blue - 500Hz.
Guitar Placement 3 :
Time Domain Analysis.

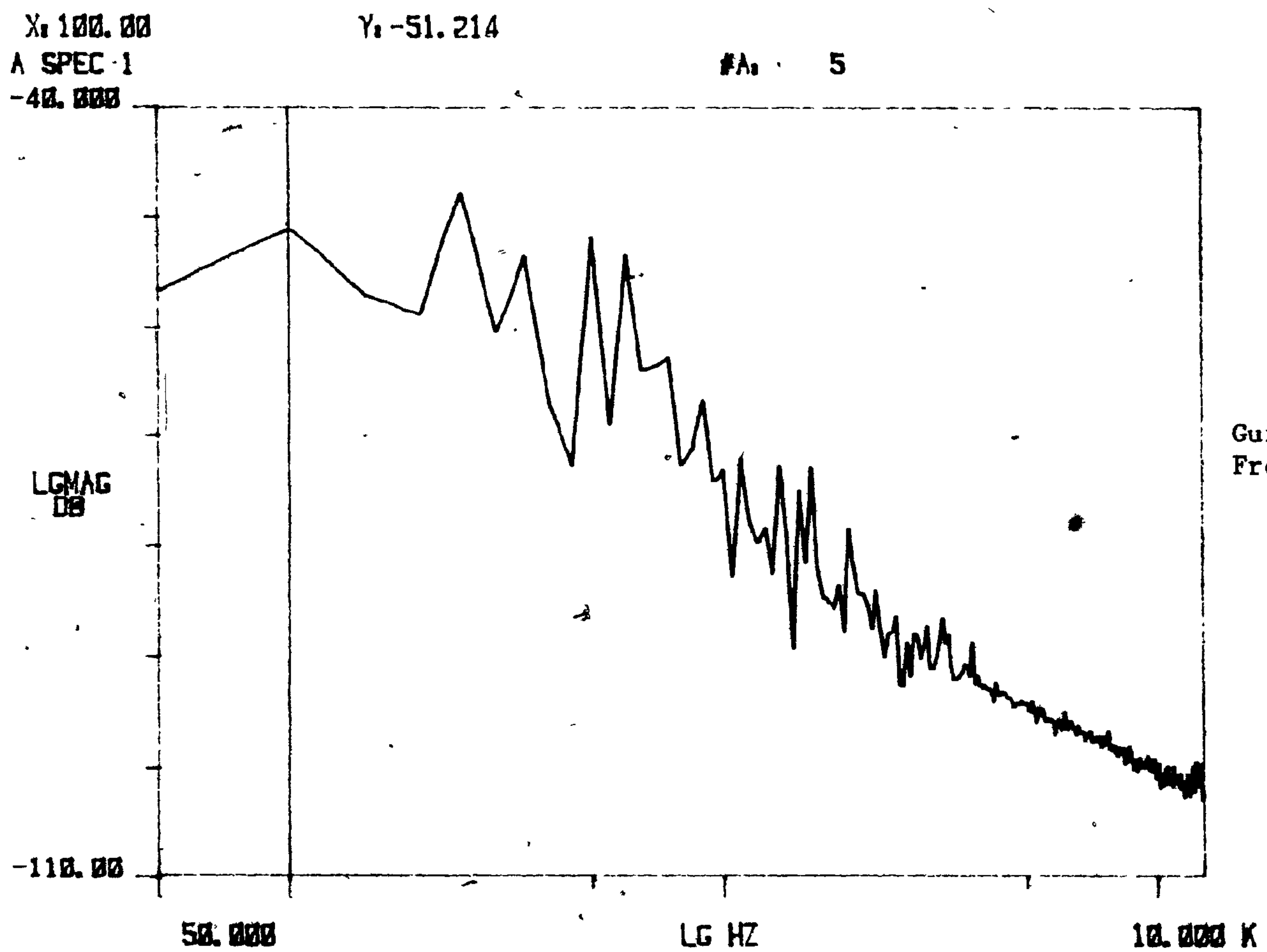

0.0
LGMAG
DB
-70.000
0.0
SEC
1.0000
Blue - 600Hz.
Green - 850Hz.
Red - 1.0KHz.



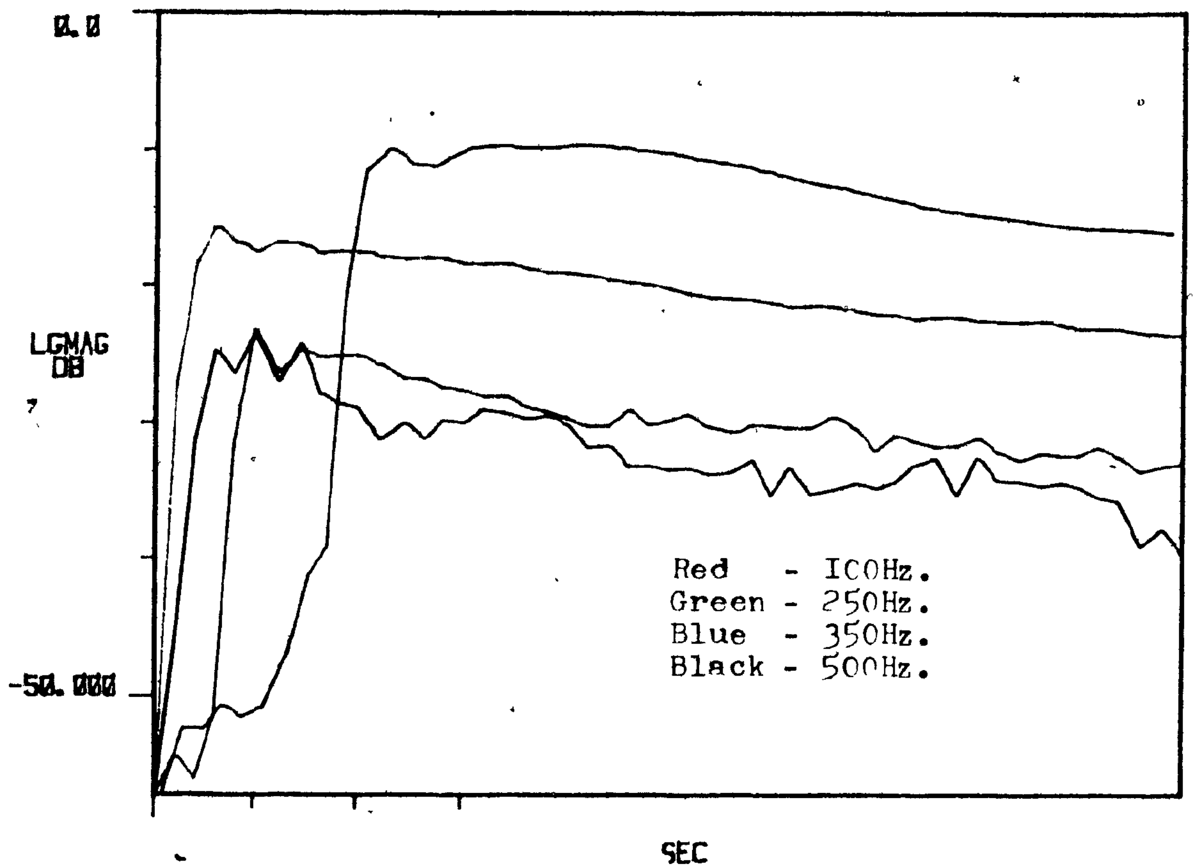
Guitar Placement (4) :
Frequency Domain Analysis.


0.0
LGMAG
DB
-60.000
SEC
Guitar Placement 4 :
Time Domain Analysis.
Green - 100Hz.
Blue - 250Hz.
Red - 350Hz.
Black - 500Hz.

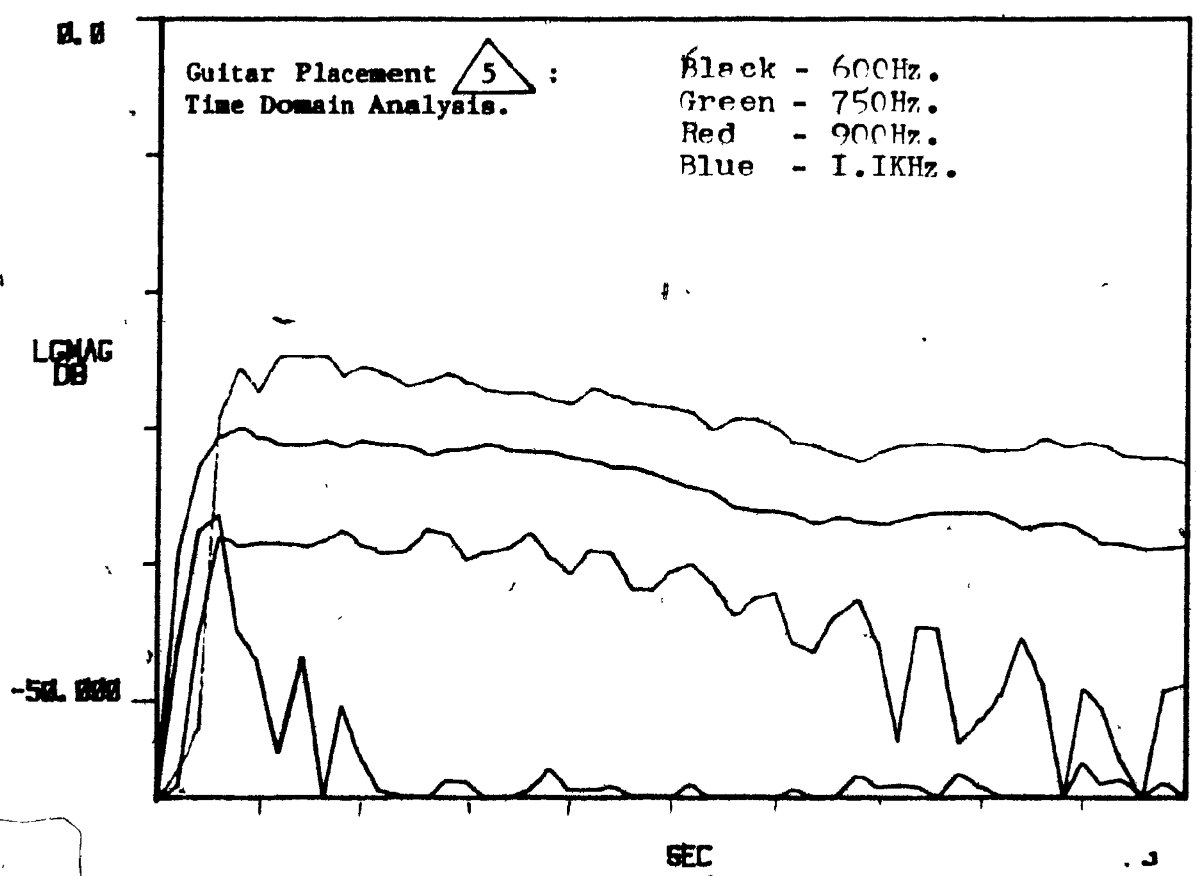

0.0
LGMAG
DB
-60.000
SEC
Black - 600Hz.
Green - 900Hz.
Blue - 1.0KHz.



Guitar Placement (5): Frequency Domain Analysis.



0.0
LGMAG DB
-50.000
SEC
Red - 100Hz.
Green - 250Hz.
Blue - 350Hz.
Black - 500Hz.



0.0
LGMAG DB
-50.000
SEC
Guitar Placement 5 :
Time Domain Analysis.
Black - 600Hz.
Green - 750Hz.
Red - 900Hz.
Blue - 1.1KHz.

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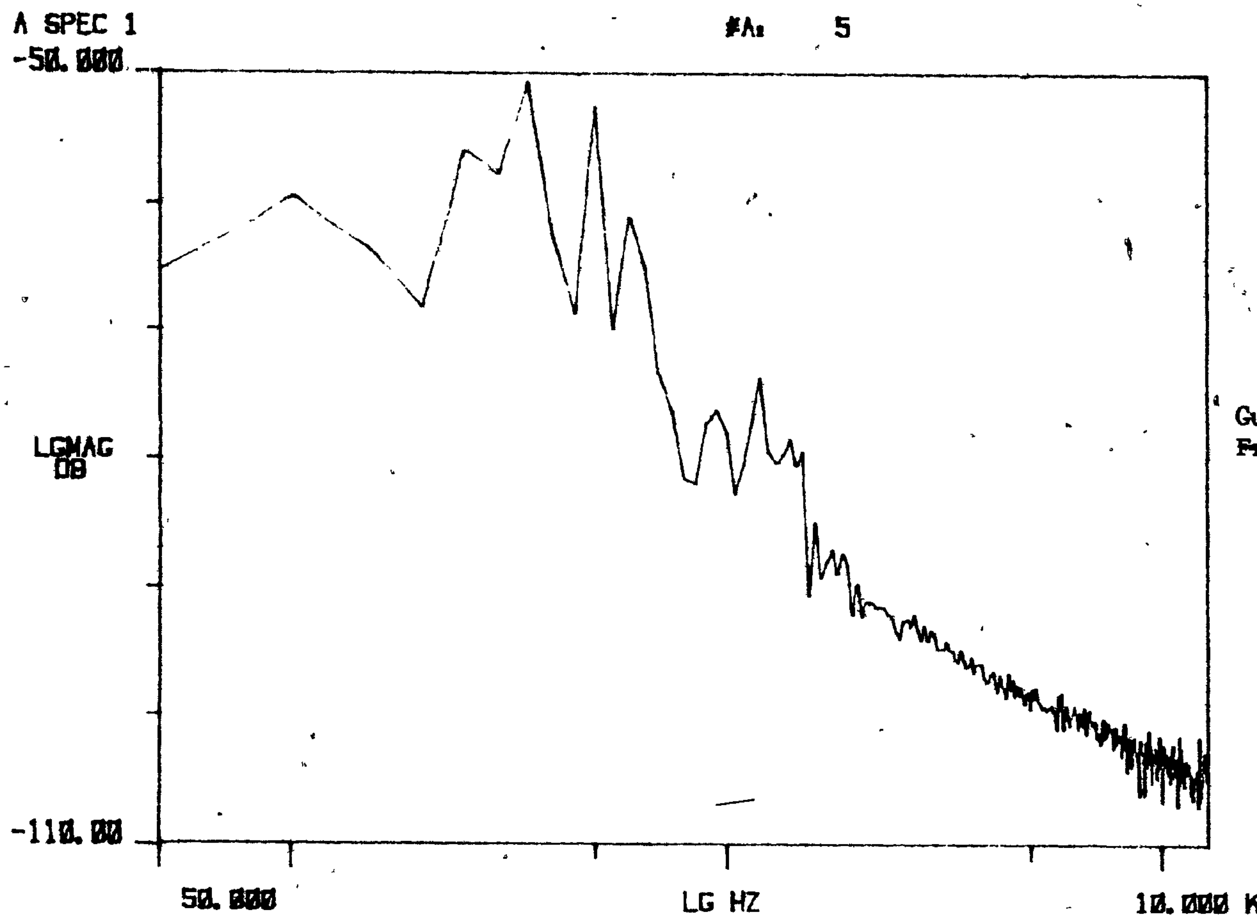
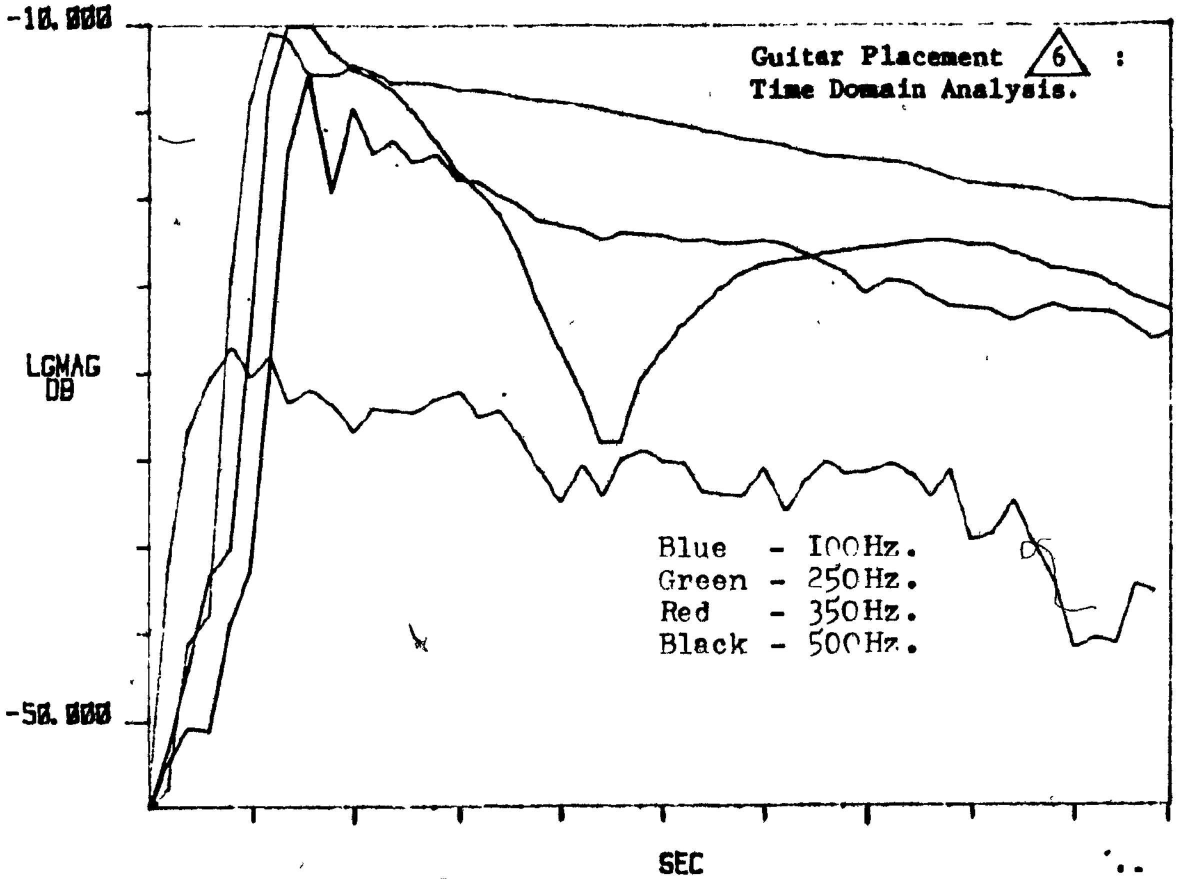
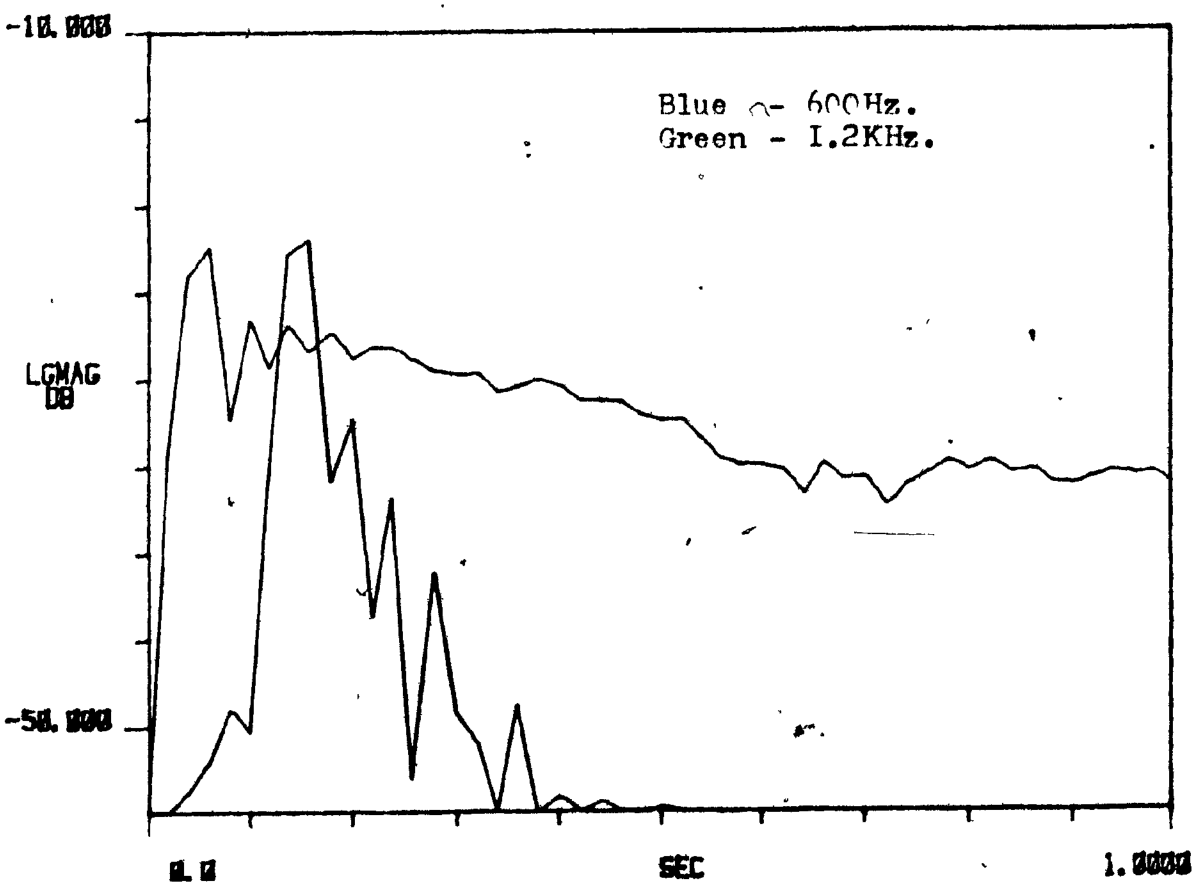
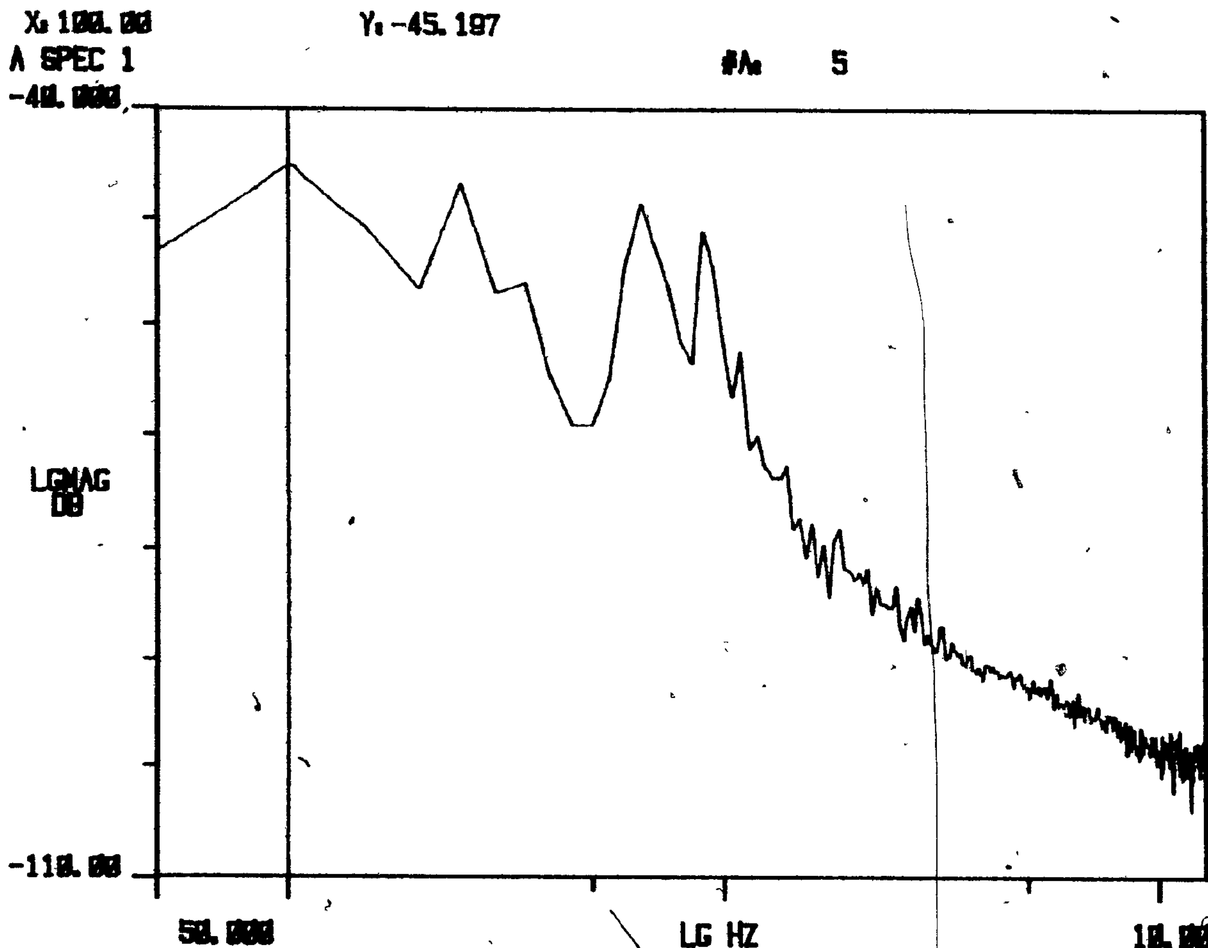


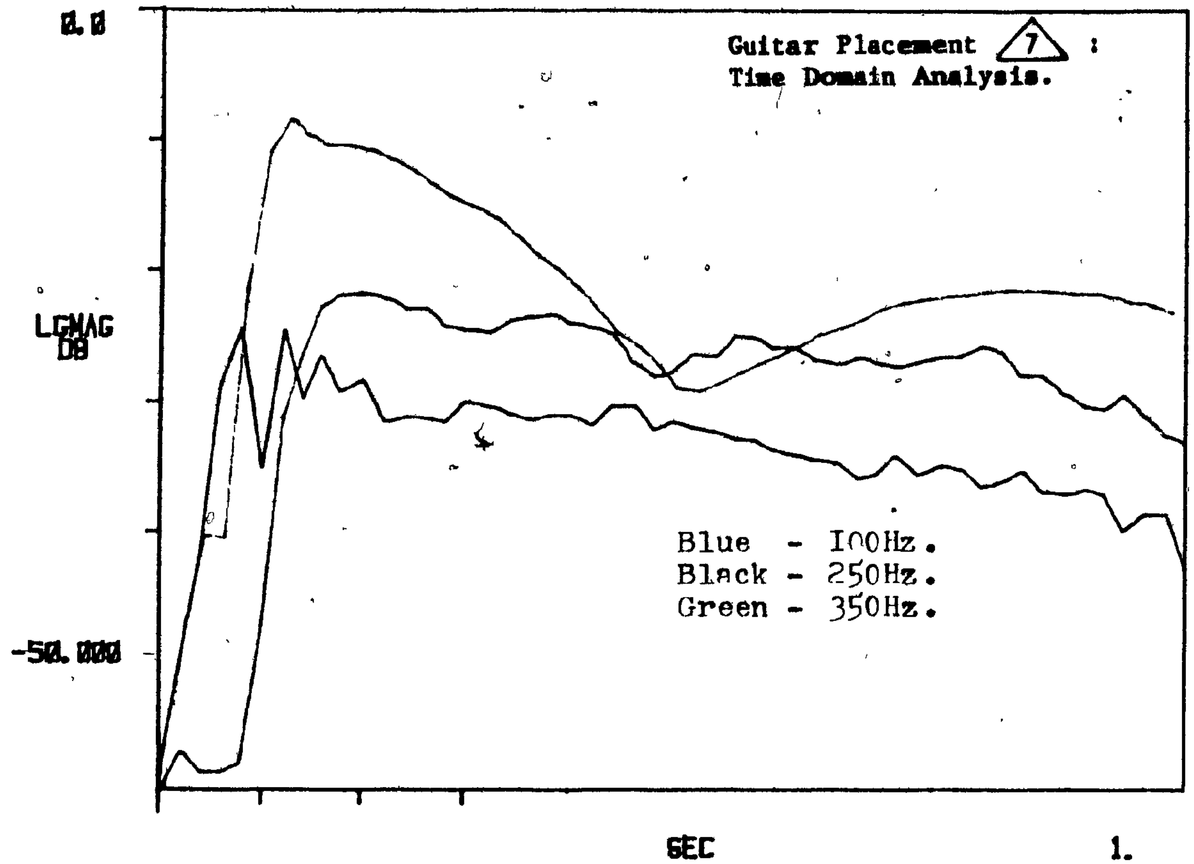
Guitar Placement 6 :
Frequency Domain Analysis.

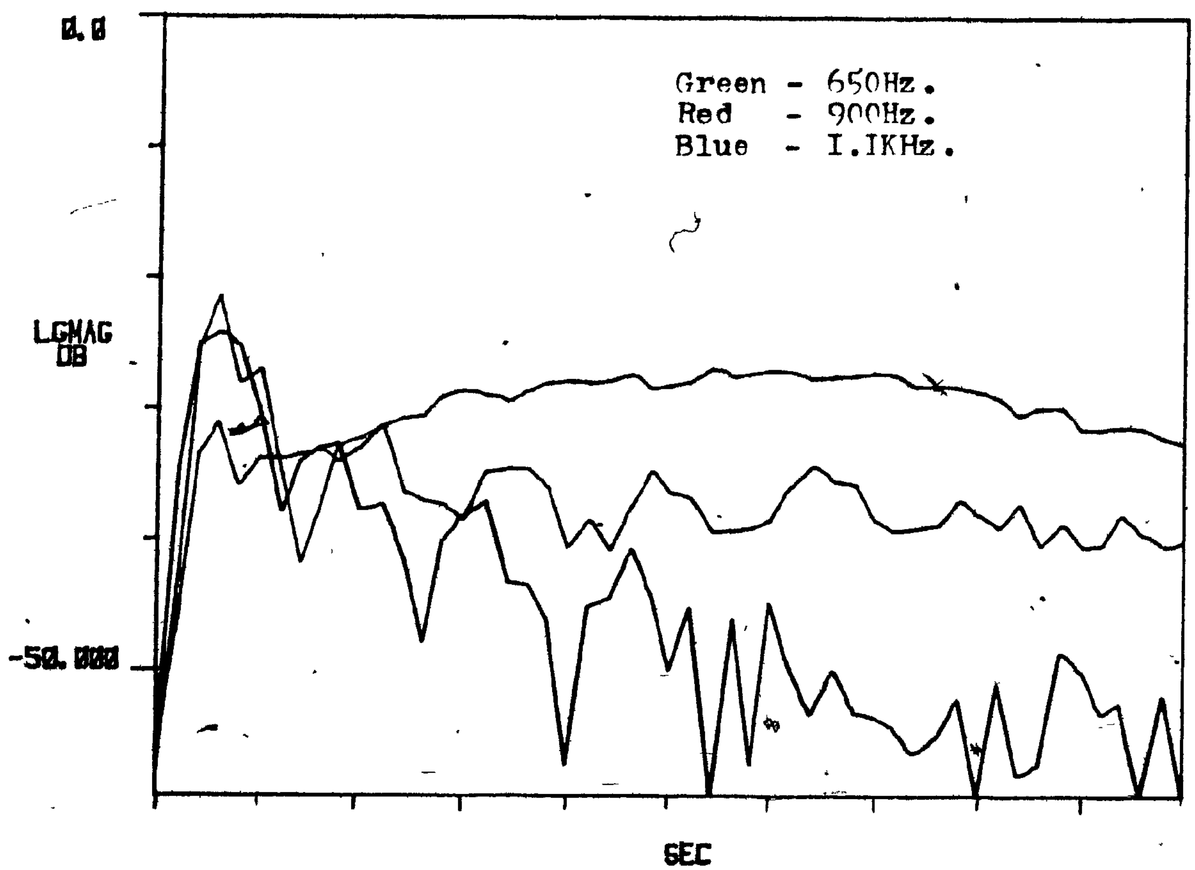

-10.000
-50.000
LGMAG DB
Guitar Placement 6 :
Time Domain Analysis.
Blue - 100Hz.
Green - 250Hz.
Red - 350Hz.
Black - 500Hz.
SEC

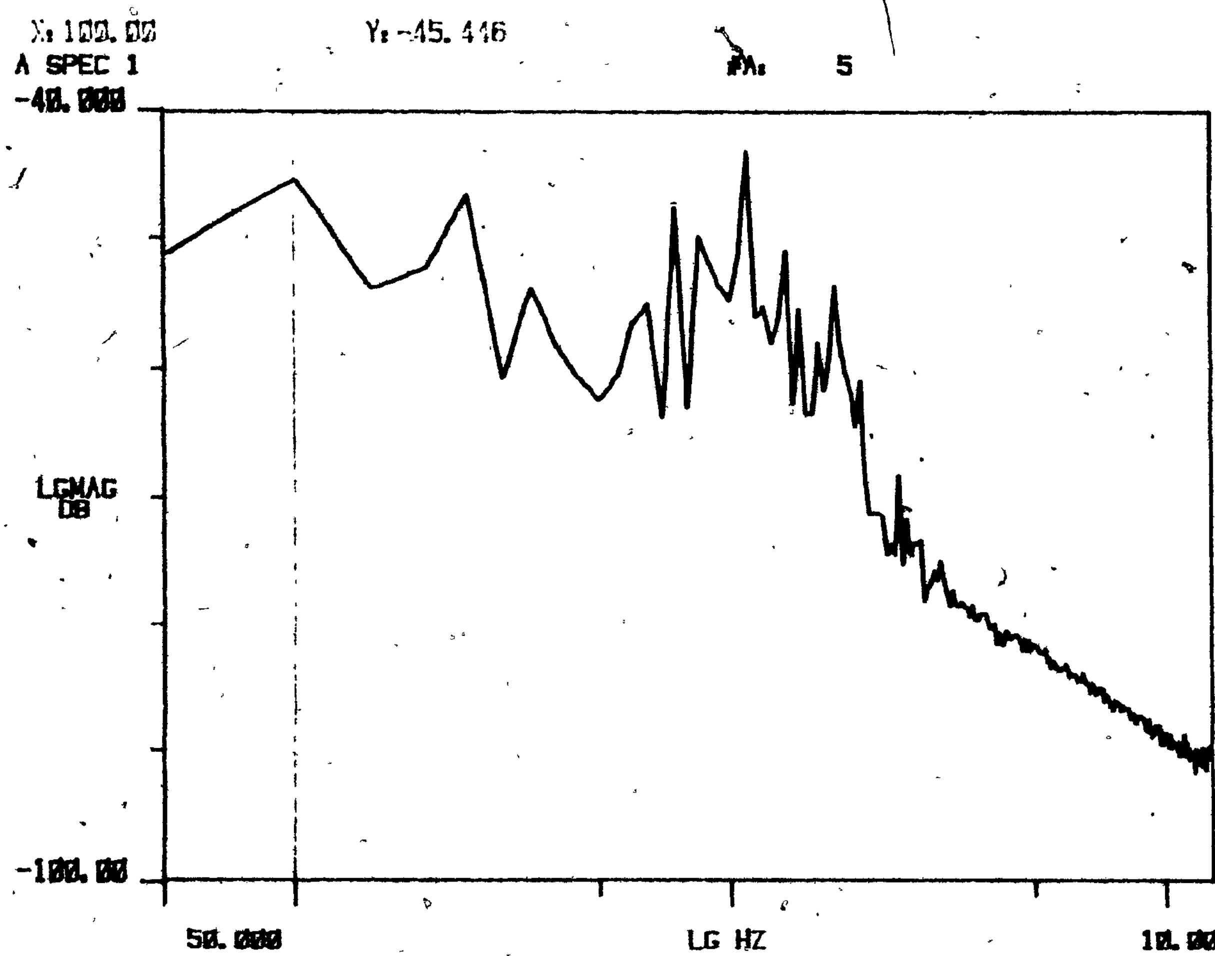

-10.000
-50.000
LGMAG DB
Blue - 600Hz.
Green - 1.2KHz.
0.0
SEC
1.0000



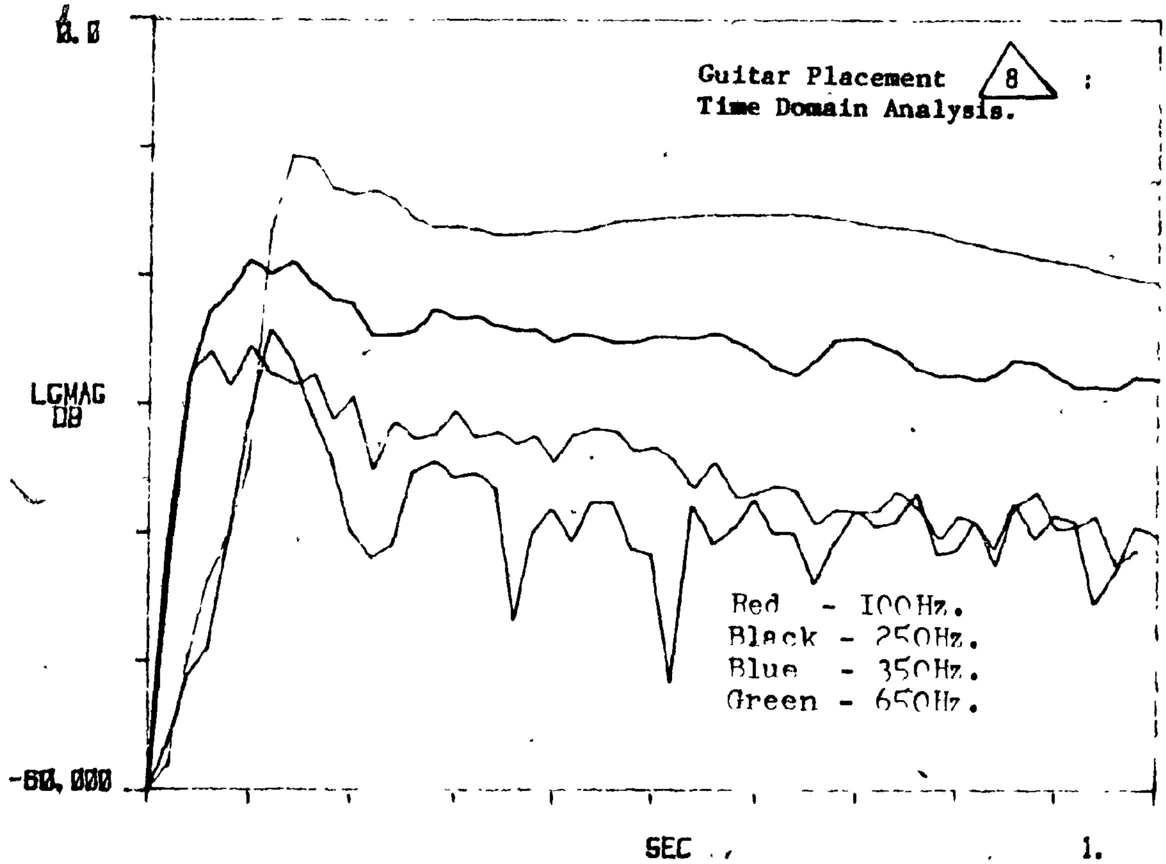
Guitar Placement 7 : Frequency Domain Analysis.

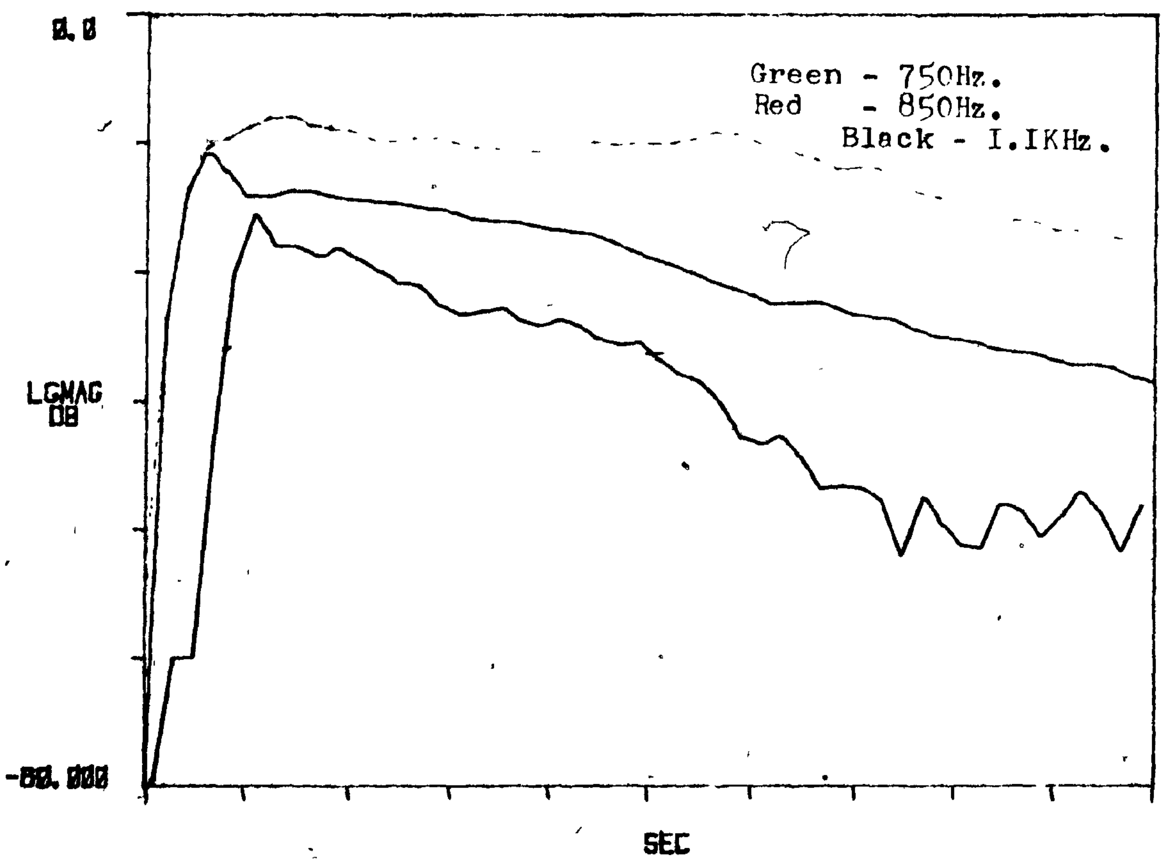

0.0
Guitar Placement 7 :
Time Domain Analysis.
LGMAG
DB
Blue - 100Hz.
Black - 250Hz.
Green - 350Hz.
-50.000
SEC
1.

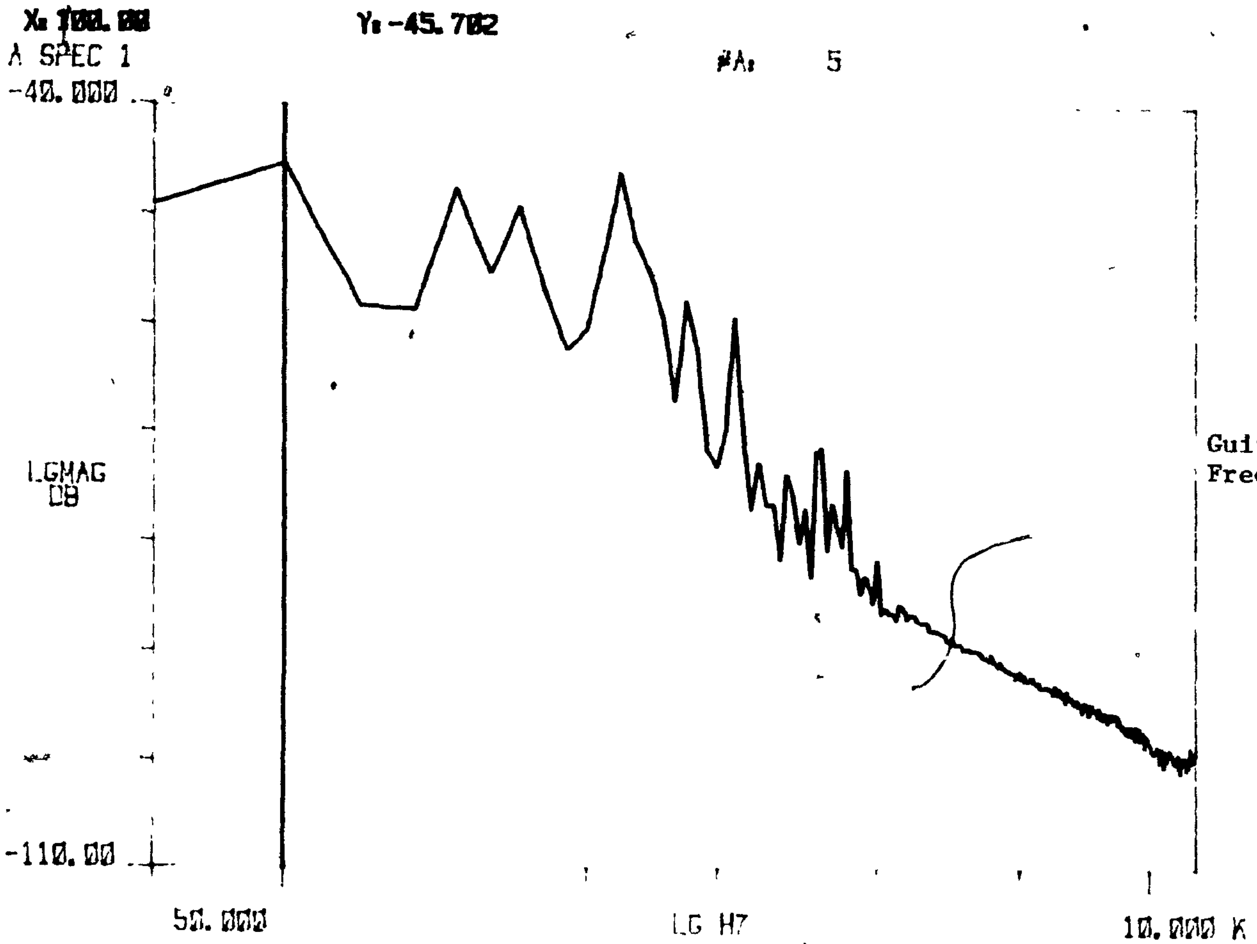

0.0
Green - 650Hz.
Red - 900Hz.
Blue - 1.1KHz.
LGMAG
DB
-50.000
SEC



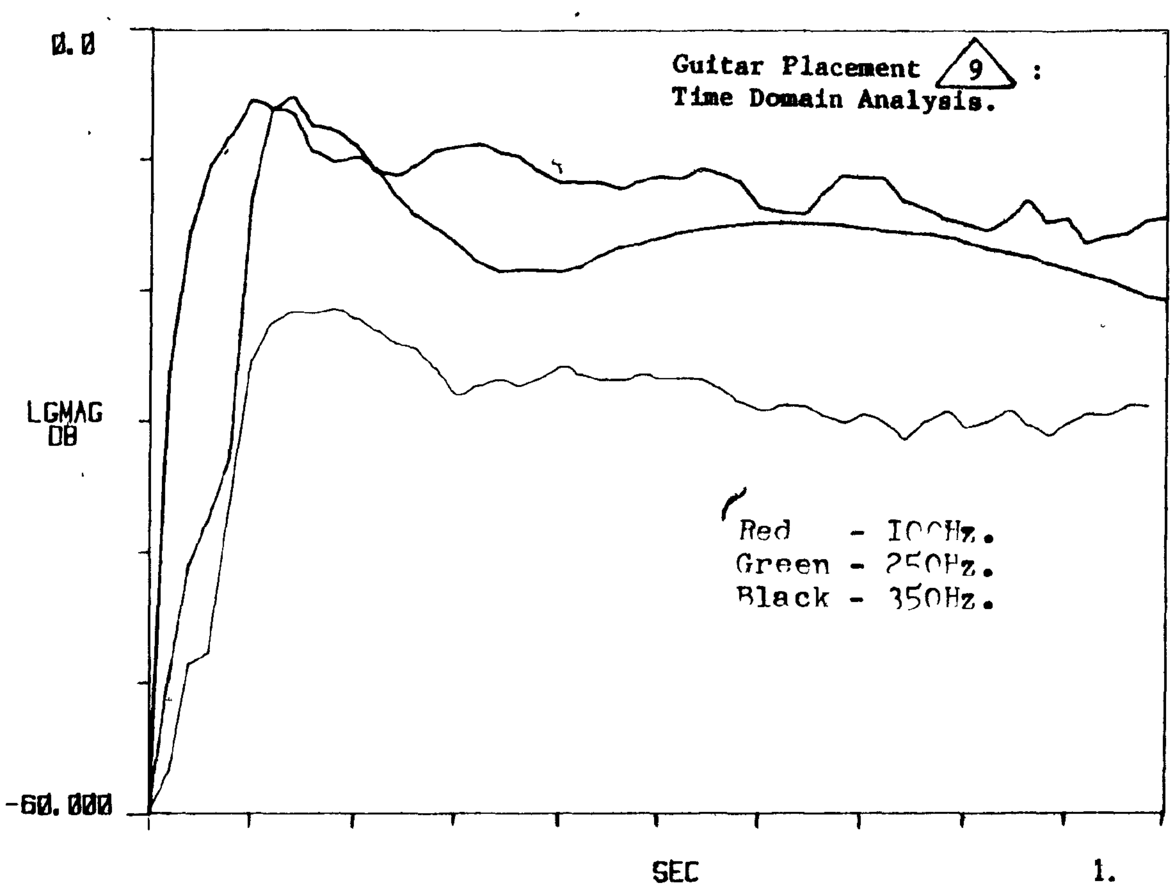
Guitar Placement 8 :
Frequency Domain Analysis.


Guitar Placement 8 :
Time Domain Analysis.
0.0
LGMAG DB
Red - 100Hz.
Black - 250Hz.
Blue - 350Hz.
Green - 650Hz.
SEC
1.

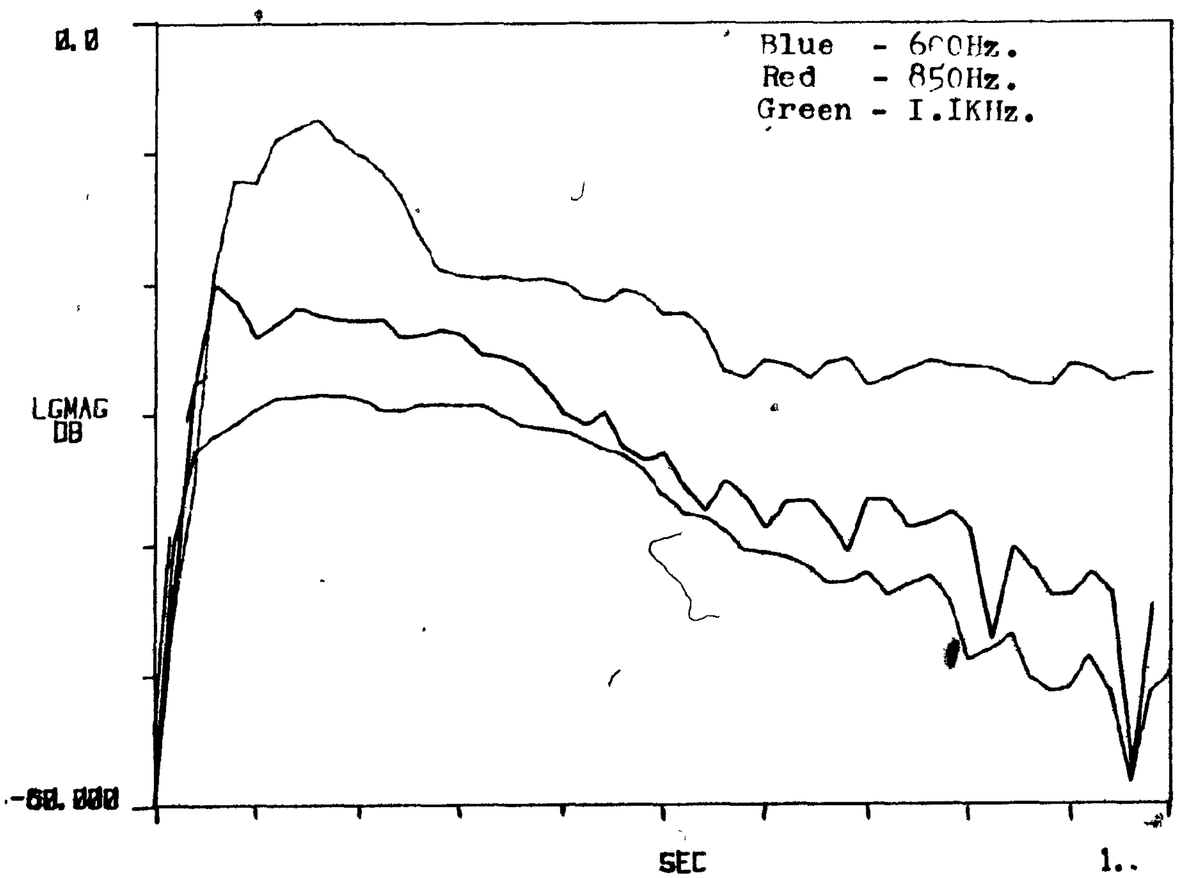

0.0
Green - 750Hz.
Red - 850Hz.
Black - I.IKHz.
LGMAG DB
-80.000
SEC



Guitar Placement (9) : Frequency Domain Analysis.



Guitar Placement 9 :
Time Domain Analysis.
0.0
LGMAG
DB
-60.000
Red - I00Hz.
Green - 250Hz.
Black - 350Hz.
SEC
1.



0.0
Blue - 600Hz.
Red - 850Hz.
Green - I.IKHz.
LGMAG
DB
-60.000
SEC
1..

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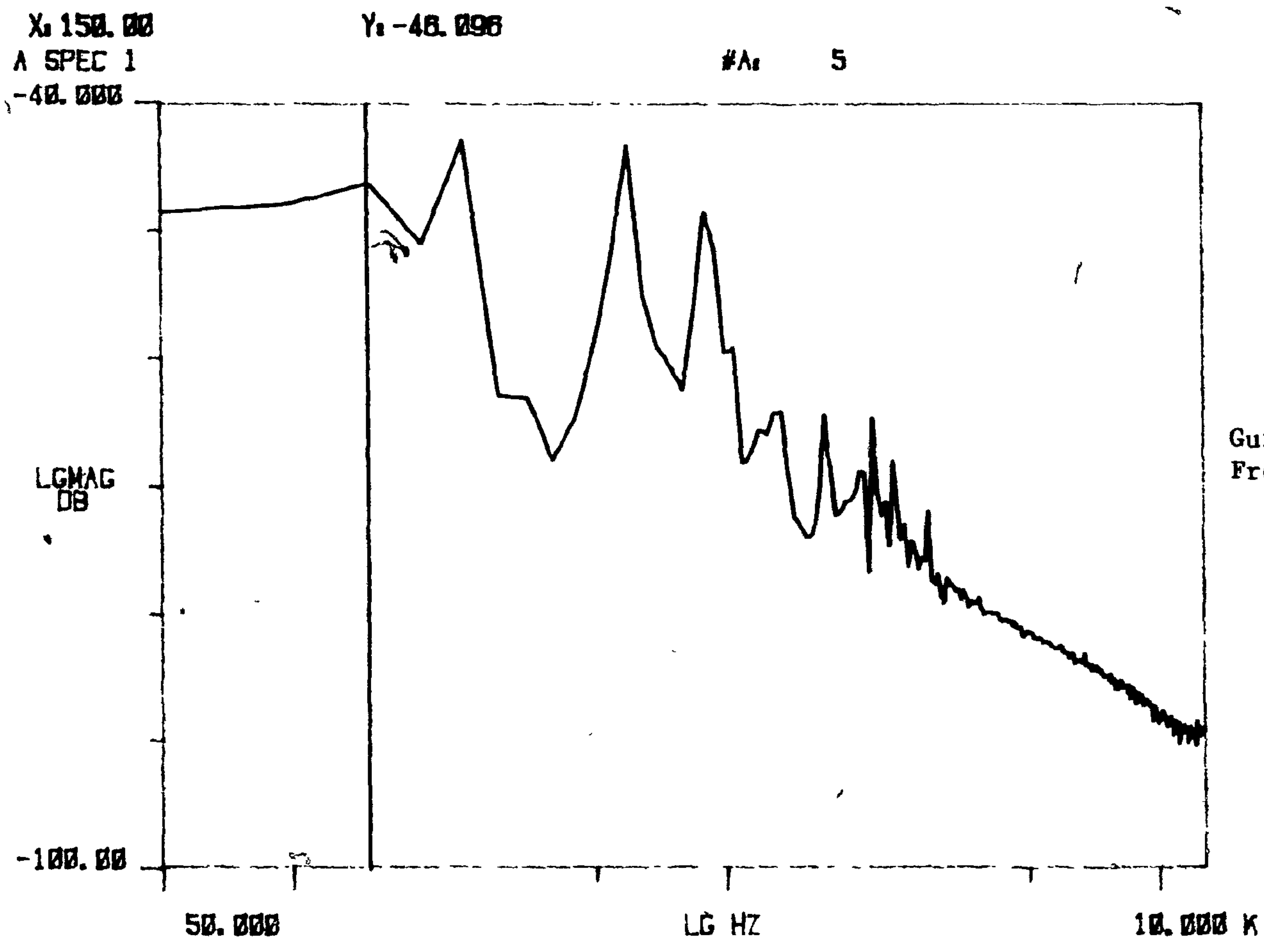
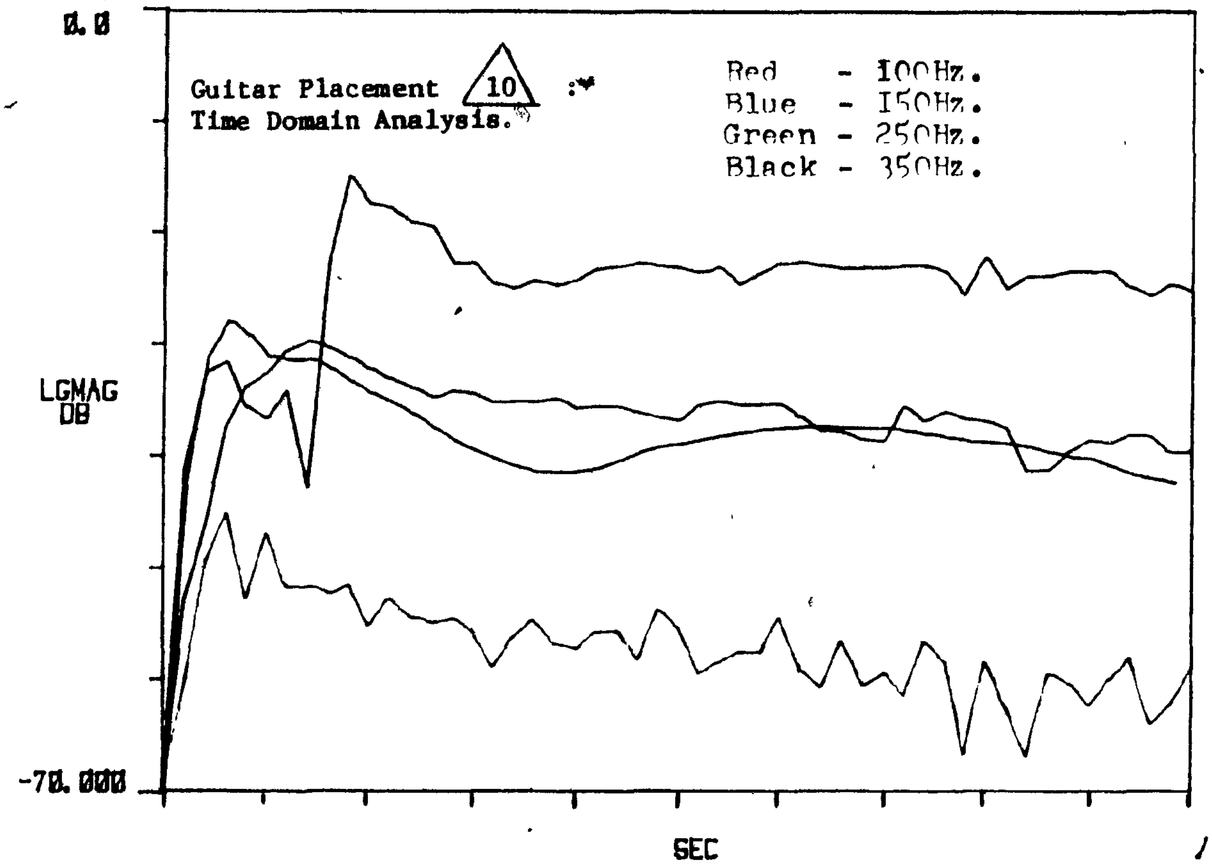
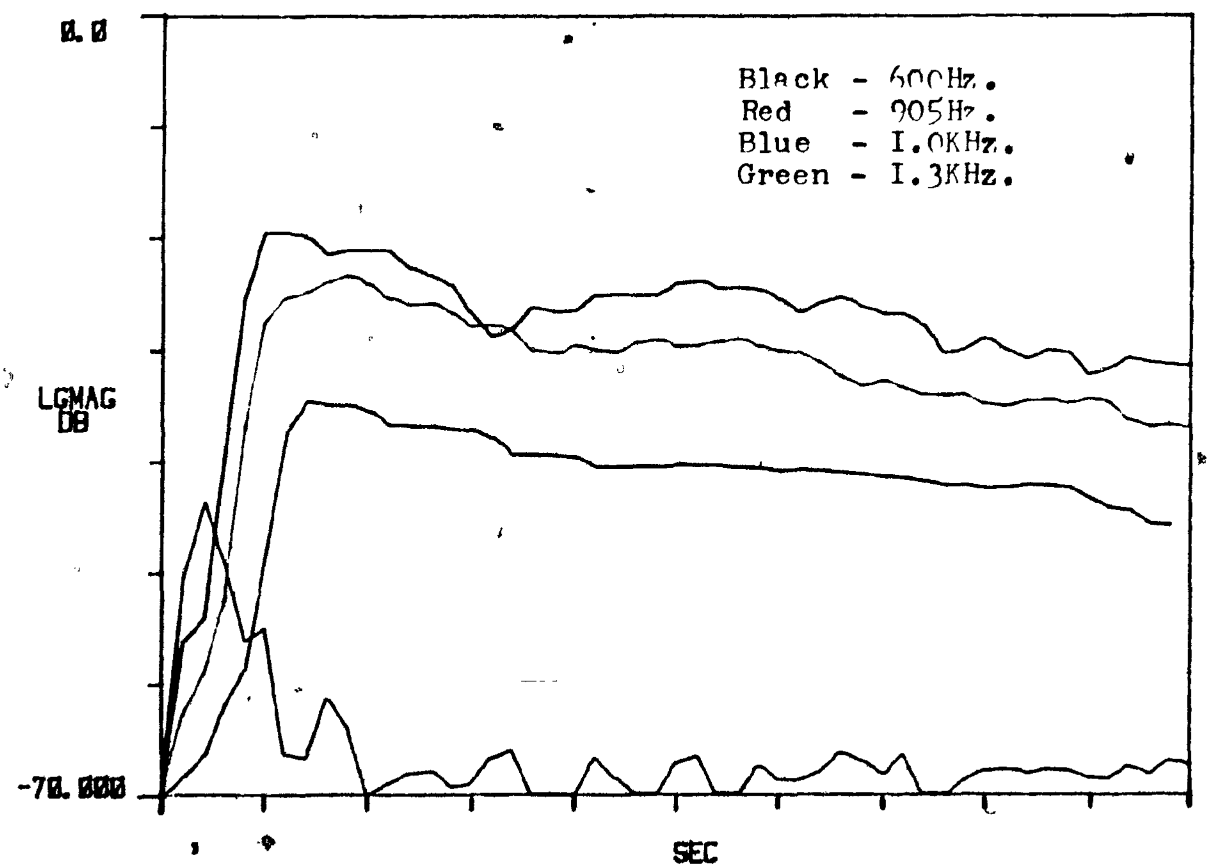


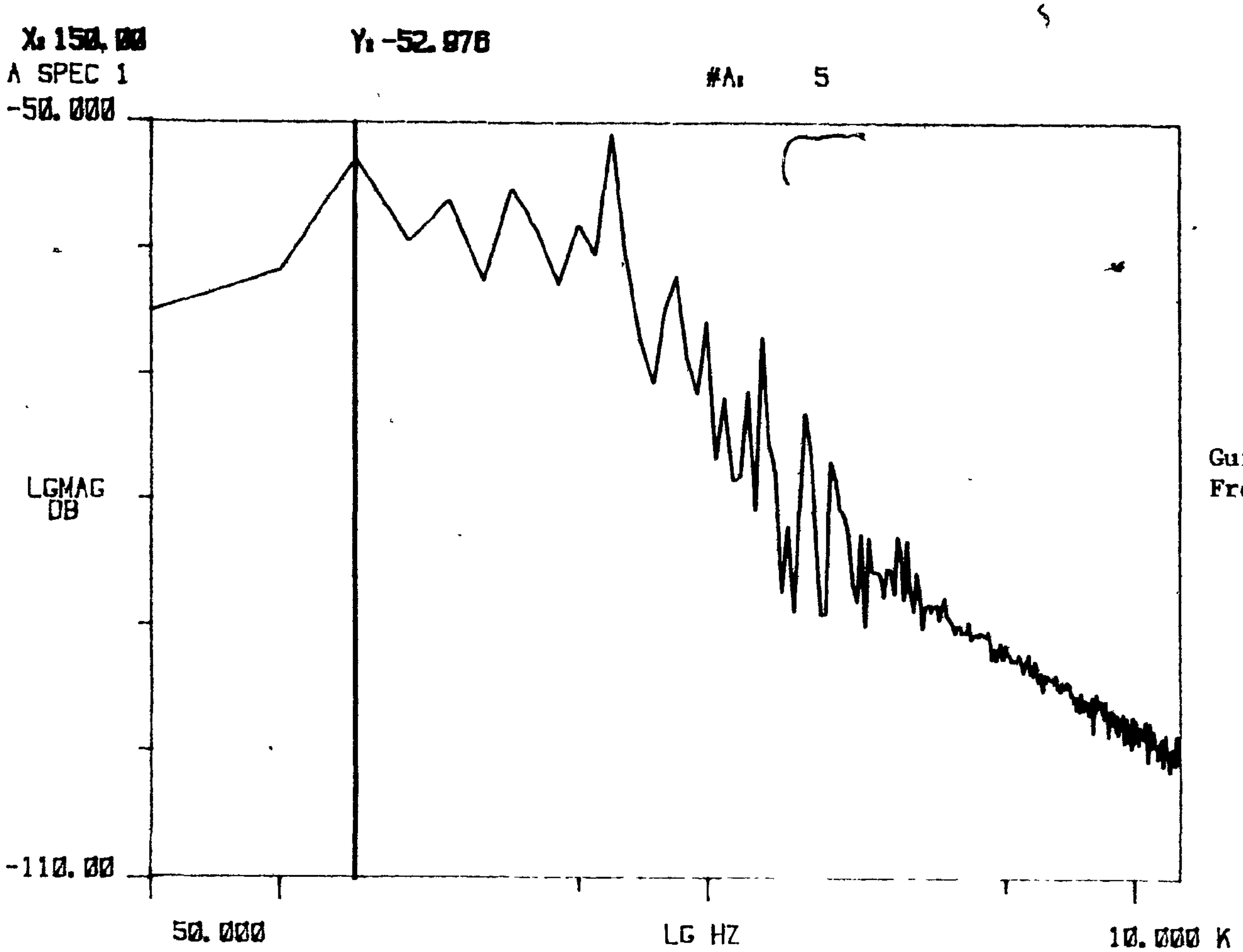
Guitar Placement (10): Frequency Domain Analysis.



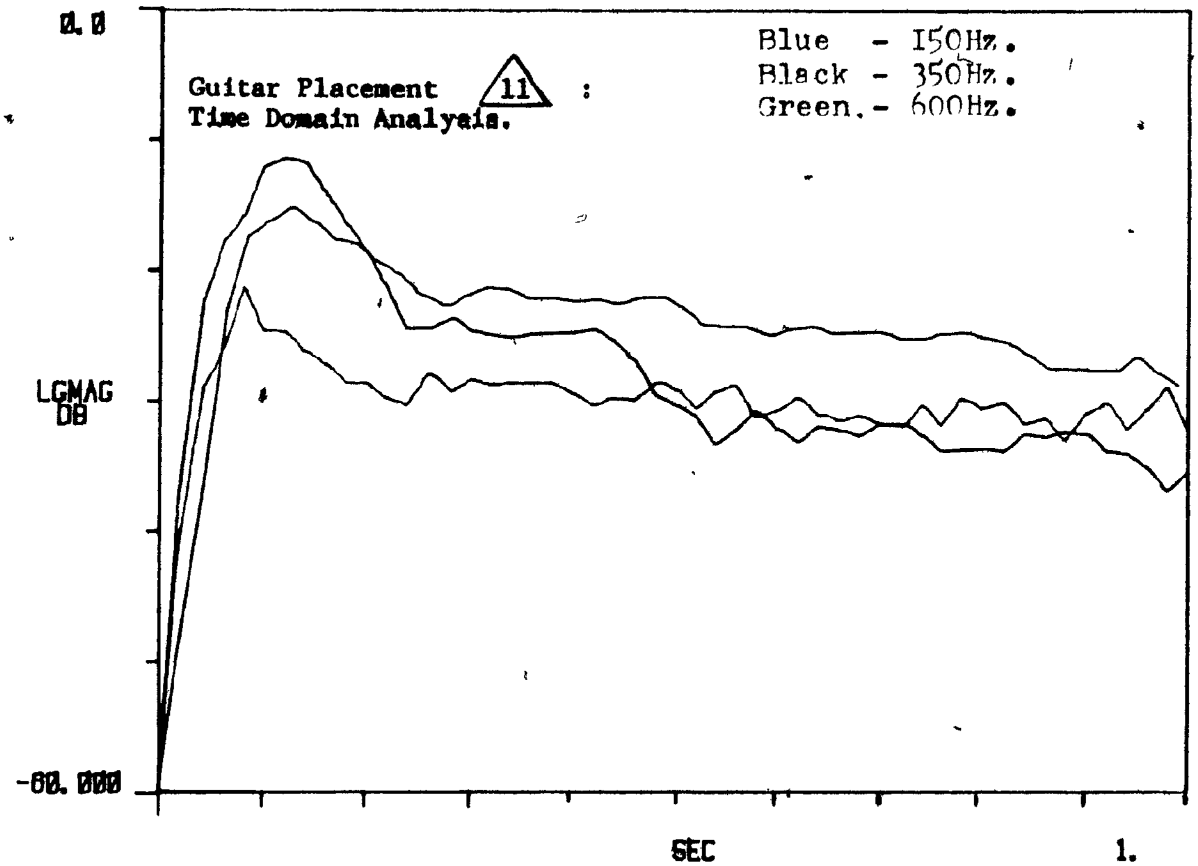
0.0
Guitar Placement 10 :
Time Domain Analysis.
Red - 100Hz.
Blue - 150Hz.
Green - 250Hz.
Black - 350Hz.
LGMAG
DB
-70.000
SEC

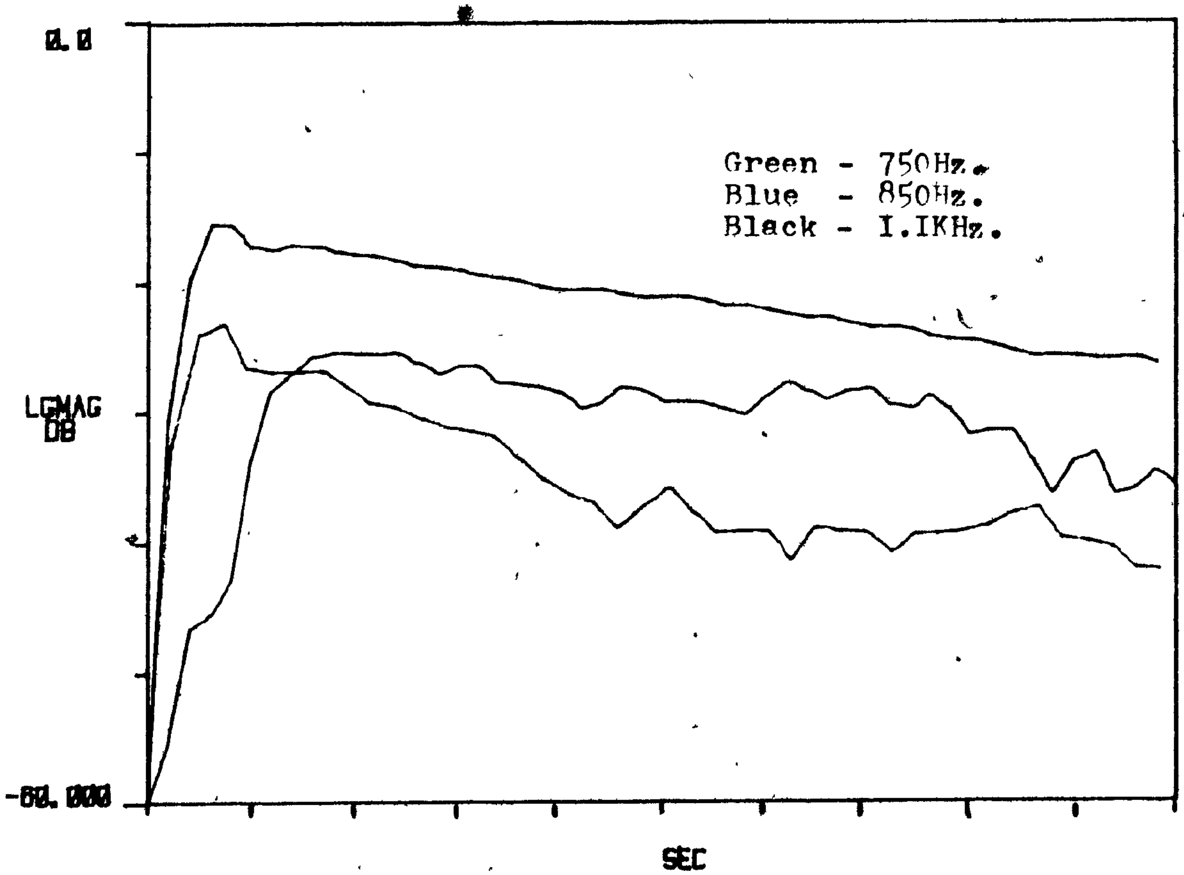


0.0
Black - 600Hz.
Red - 905Hz.
Blue - 1.0KHz.
Green - 1.3KHz.
LGMAG
DB
-70.000
SEC



Guitar Placement (11) : Frequency Domain Analysis.


0.0
Guitar Placement 11 :
Time Domain Analysis.
Blue - 150Hz.
Black - 350Hz.
Green.- 600Hz.
LGMAG
DB
-60.000
SEC
1.


0.0
Green - 750Hz.
Blue - 850Hz.
Black - 1.1KHz.
LGMAG
DB
-60.000
SEC