Tonal Considerations in the Selection of Wall Materials for Open Labial Organ Pipes

by

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SUMMARY

Research into the tonal influence of the materials in which organ pipes are fabricated, far from clarifying the question, has contributed to the confusion. The results of experiments appear at variance with the practices of organ builders and the conclusions of different workers are often uncorroborative. Due to this, in literature aimed at musicians, the question of the tonal implications of materials is dealt with superficially and often reflects the prejudices of manufacture and players.

This project aims to relate empirical understanding and analytical study, to demonstrate the tonal implications of Pipe-Metal - alloys of tin and lead - on organ pipe tone, and to investigate the possibilities of fabricating organ pipes in alternative materials.

The work includes a survey of relevant literature about other wind instruments as well as the organ, from which aspects of the controversy which require further experimental work are identified. It also shows that the experimental approach should involve the analysis of onset transient and that physical analysis should be related to the auditory capacity of humans. A method of analysis, detail of the equipment designed and the criteria for relating analysis amd physiology are presented in the text.

Experimental work, in which an organ builder was involved, investigated the influence of resonator material on steady pipe tone, the extent to which voicing operations modify tone, and the relative effects of material and wall thickness on pipe onsets. The experimental results are equated with the ideas reviewed in the initial survey and first-hand information about pipe making practice.

Conclusions indicate that only in the region c to c^2 does wall material influence tone perceptibly. The extent of wall thickness, lip material and voicing effects are conjecturally related over the whole range of open pipe frequencies, and criterion for the choice of materials for pipes of various pitches are suggested.

Finally, consideration is given to the possibilities of using other materials for pipe resonators and how new wall thickness scales might overcome tonal deficiences.

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Chapter 1.

INTRODUCTION

1.1 Reasons for the Study

Although it has long attracted the attentions of musical instrument makers and musicians, with the advent of electronic synthesis of traditional instruments and the production of some orchestral and band instruments in non-traditional materials, the effect on the tone of musical instruments of wall material has been increasingly discussed and research work carried out. Despite the experiments of studious workers, the question is still far from resolved: it is not clear from studies of organ pipe resonator materials, whether or not material does in fact influence the tone, since the reports of different researchers do not corroborate each others findings. Furthermore, the practices of organ builders are at variance with experimental conclusions. It is not surprising therefore, that otherwise scholarly literature about instruments and musical acoustics aimed at musicians, fails to present a clear picture of this aspect of instrument design, reflecting instead the prejudices held by musicians and instrument makers alike. The project is undertaken by a musician keen to understand the relationship between empirical and acoustic reasons for the choice of materials.

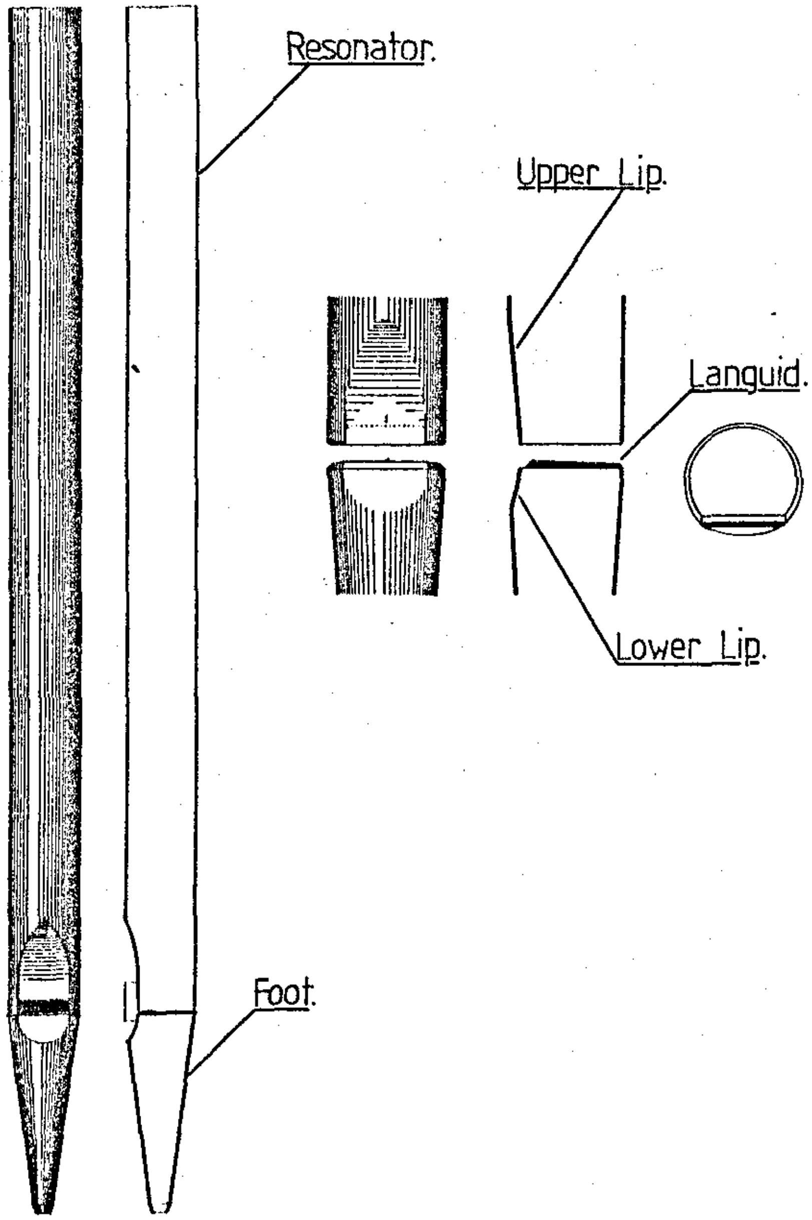

Fig. 1.1 Open Labial Organ Pipe.

1.2 Labial Organ Pipes and Their Materials

Physical differences in pipe design divide organ stops into lingual or reed stops in which a vibrating tongue initiates movement of the air in the resonator, and labial or flue stops wherein the lip is stationary and the air passing it excites the standing wave in the resonator. It is this type of pipe which is considered in this project. The parts of a labial pipe are shown in figure 1.1 . Labial stops, which dominate the specifications of most organs, may be divided into three broad classifications according to the length/cross-sectional-area ratio, or 'scale' of the stop. So called string tones are elicited from narrow scaled stops, and from wide ones, flute tone. Between these extremes is the dominant organ tone colour, produced by intermediate scaled labial pipes, called diapasons.

Cylindrical organ pipes are usually made in alloys of lead and tin referred to as pipe-metal, though large pipes are often made from zinc sheet. Pipe metal alloys rich in tin have a plain bright appearance, and those rich in lead, a dull grey finish. Between about 40 per cent and 80 per cent tin content however, the metal has a spotted appearance attributable to the alloy's lack of homogeneity. The spots, whose cores are rich in lead and outer edges rich in tin, are joined in a net-like structure of eutectic material which is much stronger than the material of the spots themselves. The metal has a low melting point: 183° C for 70 per cent tin and 30 per cent lead alloys. Sheets are cast and the metal is thicknessed by planing . Rolling softens the alloys which are already near the limit of softness for practical purposes. The sheets are easily formed around mandrils into cylinders and are readily joined by soft soldering.

1.3 Scope of the Work

By building on the basis of pertinent acoustical reports about organ pipes and other instruments, using ideas set out in musical literature and collecting first-hand information about organ building practice, a comprehensive survey is made of research and debate about materials and musical tone quality. Those aspects of the controversy which require further experimental work for clarification are thus defined. Further consideration is given to the method of studying these and to the experimental techniques involved, before a programme of experiments is decided. The results of the experiments are combined with the ideas reviewed initially, and an overall picture of the tonal influence of wall materials on open labial pipes, relative to the influence of other factors, is formed.

The study has three objectives:

1. To relate empirical understanding and practice to analytical and experimental work.
2. To demonstrate the tonal implications of pipe metal on organ pipes.
3. To investigate the possibilities of fabricating organ pipes in alternative materials.

Chapter 2.

BACKGROUND

2.1 Introduction

Serious study and articulate debate about the role the materials from which musical instruments are made has in determining tone quality, is far from new in attracting the attention of researchers. Although a paper by Biot[1] is probably the first published report, the question has been of importance to instrument makers and musicians from earlier times. Organ builders in particular, and also flute and other woodwind manufacturers, have investigated the properties of new materials to assess their suitability for instrument fabrication.

The myths surrounding manufacturing practice, together with the prejudices of players and musical writers, have contributed to the debate by attracting attention to the points at issue. Whilst contributing valuable knowledge and practical skills, they have often frustrated attempts to resolve the questions. Many of the studies relevant here are from recent years. Since the second world war more powerful methods have been available for the study of tone-quality in the form of dedicated computers and spectrum analysers. Knowledge from experimental psychology about subjective judgements has also made new acoustic studies viable.

Although organ pipes figure prominently among investigations into the effect of materials on musical instrument tone quality,[2] and studies of organ tone contribute considerably to the total body of knowledge about the acoustics of music, studies of other instruments are relevant to this study and are included in this review. Other than the effect of material on pipe-tone, consideration is given to studies which have produced information about the voicing process,[3] transients,[4] and wall vibrations,[5] as well as data on the characteristics of particular pipe tones.[6]

[1] Miller (85) 164

[2] Miller (85) Lottermoser (70) Boner & Neuman (15) Glatter-Gotz (46) Lottermoser & Meyer (72) Lottermoser & Meyer (73) Backus & Hundley (3)

[3] Mercer (79) Mercer (81) Meyer (83) Danzer (32) Rakowsi & Richardson (101)

[4] Fletcher (40) Caddy & Pollard (20) Keeler (61) Nolle & Boner (89)

[5] Benade (11) Backus & Hundley (9)

[6] Fletcher, Blackmen & Christensen (43) Boner (14) Meyer (84) Tanner (116)

Theoretical and experimental considerations of the pipes' sound producing mechanism,[1] studies on theoretical aspects of construction,[2] and external influences including architecture on organ tone[3] are other areas from which information has been collected. Among studies of other instruments considered, wind tone, including transients, has figured prominently.[4] In common with the organ, a lot of work has been carried out on the influence of wall material on woodwind tone.[5]

Literature from musical and scientific sources, which reflects both serious study and also prejudice, is reviewed here. The previous work is evaluated and aspects which appertain directly to the relationship between sound and materials are considered and discussed in relation to the current work. Also presented is an appraisal of organ building practice as it effects the choice of materials and, in the organ builders estimation at least, the tone of the instrument. In the sections' conclusion, the review is used to identify areas where knowledge is lacking, development possible or where approach should differ. The implications of each are outlined. The way each has influenced previous work and the role it should have in this and further work considered.

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[1] Coltman (25) Fletcher (39) Norman (90)
Powell (99) Bawtree (8) Bonavia-Hunt (17)
Elder (36)

[2] Fletcher (42) Ingersleu & Frobenius (55)

[3] Pollard (77) Rienstra (104)

[4] Richardson (102) Luce & Clark (75)
Strong & Clark (113) Freedman (44)
Beauchamp (10)

[5] Hall (49) Coltman (26) Backus (2)
Miller (86) Parker (94)

2.2 Musical Literature

The interest of musicians in the historical and tonal development of instruments is reflected by the number of scholarly books and articles in journals about instruments. This is due partly to an appetite for the performance of classical and romantic music as it would have been played in its composer's day, and to a curiosity about the tonal value of traditional materials brought about by the adoption of new materials for orchestral instruments such as recorders, clarinets and sousaphones, and also for reconstructions of ancient instruments such as krumhorns, and bagpipes. Unfortunately, confusion about the influence of material on tone has been perpetuated by otherwise authorative writers who more often reflect the prejudices of players and instrument makers rather than entering into more complex and less definitive discussions involving the evidence of those who have seriously set out to shed light on the controversy.

The following statement by Jeans[1] illustrates the sort of unsubstantiated remarks which are made:

" Organ builders usually specify the precise nature of the metal or wood of which their pipes are to be built, the reasons being that the quality of tone depends on the material of the pipe. For instance, pipes of wood produce a heavier, but also a warmer and more mellow tone than pipes of metal, while pipes of nearly pure tin produce a richer tone than pipes of cheaper metal; a silver clarinet sounds very different from one of wood, just as an orchestral flute sounds different from a penny whistle. "

Certainly the absurdity of the final argument is surprising from this author. It is not untrue that exponents of the orchestral flute elicit from their intruments sounds dissimilar to those usually produced by a penny whistle, but equally, a flautist will find marked differences in the timbre of any two flutes, even if both are silver. Other than this, three significant points emerge from Jeans' statement. First, acknowledging the care taken by organ builders in the choice of materials, he subscribes to the supposition that pipe tone and materials

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[1] Jeans (56) 147

are inextricably linked. This is the predominant opinion amongst authors, most of whom also agree about the value of tin pipes. Barnes[1] writes;

" Of all the materials used in the construction of organ pipes, that which ranks first in point of excellence is pure tin. It is almost indispensable in the production of keener toned stops. For duller toned pipes..... a very large percentage of lead is introduced. "

Sumner[2] cites as an example of this the work of Silberman and Cavillé-Coll, who used alloys of over 95 per cent tin for their narrow scaled, harmonically rich flue pipes, though he is unable to substantiate his claim, that silver and gold are inferior to pipe metal for organ pipes.

Audsley, despite his statement that, " there are few matters more important in an organ than the quality of the metal used in the construction of the pipes, " writes;[3]

" We have heard tones in every way satisfactory produced from pipes constructed of practically all classes of pipe metal and alloys - from the poorest alloy of lead and antimony, to the richest alloy of tin and lead. We have heard the most perfect imitations of the violin and violincello produced from pipes of spotted-metal; such imitative tones as we have never heard from pipes of tin. "[4]

Two examples are found of musical writers using the results of experimenters work to support the notions of instrument makers although the conclusions to the studies state otherwise. Despite their findings, the results of a paper by Boner and Newman[5] have been used to argue that wall material does effect the tone both of organ pipes[6] and also the oboe.[7] Sumner[8] states;

" A physical analysis of the effect of pipe materials on tone quality has confirmed what artist organ builders have found in centuries of empiricism. Of the various alloys used in the experiments, a fifty-fifty mixture of tin and lead gave the best reinforcement of the first seven harmonics, with wood second and galvanised iron and other materials far behind. Steel only served to reinforce the eighth to the eleventh partials. "

[1] Barnes (5) 30-33

[2] Sumner (114) 277

[3] Audsley (7) 501

[4] Audsley (7) 509

[5] Boner & Newman (15)

[6] Sumner (114)

[7] Bate (6) 131

[8] Sumner (114) 277

Boner and Newman however, used one alloy only which they refer to as regular pipe metal[1] and which they intimate contains a larger quantity of lead than tin. They concluded that there was very little difference in the steady analysis and even listening tests revealed very small audible differences.

Anthony Wood[2] refers to this article and states:

" It has sometimes been held that the sound produced by an air-cavity such as an organ pipe depends only on the geometric form of the cavity. This view has never been popular among musicians, and has now been universally abandoned. The material of which a pipe is made does affect the quality and, for pipes identical in shape and size, the pitch. In general terms it is agreed that there is justification for the views of organ builders who claim that heavy lead alloys emphasize the lower partial tones, where as with zinc the higher partials are amplified and the quality of the tone is brighter and more strident. The results of attempts so far made to confirm this view by physical analysis show clearly that the material used does affect the quality, although the measurements indicate less decisive differences than might have been anticipated. "

Bowsher's revision of Dr. Wood's book (1961) contains a footnote referring to a contradictory view set out by Knauss and Yeager[3] who maintain that wall material has no effect on the tone quality of the cornet.

The second point arising from Jeans' statement, concerns the relative merits of wood and metal pipes. Those authors who illustrate the extent to which pipe tone depends on material by contrasting the tone of wood pipes with metal ones (Sumner and Williams are among them) must note that metal pipes are commonly construction as cylindrical tubes which have physical modes of vibration so different to those associated with the angular tubes of wooden pipes, that tonal comparison is quite impossible.[4]

Lastly, Jeans' statement illustrates the psycho-economic factor involved with a musician's comprehension of musical sounds. Although this factor is of less importance for organ pipes than for any other instrument, it is interesting that rich tone is associated with expensive metal. In a similar way, visual considerations might account for the impressive

[1] Boner & Newman (15) 86

[2] Wood (130) 124

[3] Knauss & Yeager (63)

[4] Nolle & Boner (89)

burnished tin pipes which form the front screen of many continental organ facades.

The modification of pipe tone possible by voicing is not commented upon by many musical writers. Audsley[1] emphasises the importance of careful voicing: a point which Sumner[2] takes up when discussing the use of zinc pipes. He maintains that, " in the hands of any but a skillful voicer it (zinc) tends to produce a hard, desiccated and hungry tone, " and therefore infers that a variety of tone is possible from any particular pipe and that this can be adjusted by voicing.

The large number of references to organ pipe material and tone certainly reflects the interest of musicians in the subject, but reflected also, in the studies themselves, are the traditions of instrument makers and the aesthetic prejudices of musicians and admirers. It is correct for instance, that the assumptions about the importance of tin should be presented, substantiated only by the practices of organ builders, but to ignore works which attempt to clarify its role by scientific study shows a reserve which borders on prejudice. The misconstruction of experimental results also exemplifies this. The variety of tone possible from pipes is not debated to any extent, but there is a certain lack of unanimity about the association of particular tones with specific metal alloys.

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[1] Audsley (7)

[2] Sumner (114)

2.3 Scientific Studies

2.3.1 Wind Instruments in General

Despite experimental work on the influence of wall materials on various wind instruments, clear answers about the role of materials in achieving a particular timbre are not found. Instead, a variety of opinions are expressed reminiscent of the confusion and lack of agreement found in the literature from more musically biased sources.

Perhaps it was the success of Boehm's flutes, made in hard drawn silver at a time when flutes were only made in wood, which has led to our questioning whether material does effect the tone of musical instruments, especially since Boehm also made flutes in wood. He had little doubt of the influence of material on tone:

" The greater or less hardness and brittleness of the material has a very great effect upon the quality of tone. Upon this point much experience is at hand. Tubes of pewter give the softest, and at the same time the weakest, tones; those made of very hard and brittle German silver have, on the contrary, the most brilliant, but also the shrillest, tones; the silver flute is preferable because of its unsurpassed brilliancy and sonorousness; compared with these, the tones of flutes made of wood, sound literally wooden. "

The eminent professor Carl von Schafhautl, who worked with Boehm at the University of Munich, in 1879 described how he made seven cavalry trumpets with internal dimensions exactly alike, but different thicknesses in brass, lead and gypsum sheet as well as three types of paper having different thicknesses. They were blown by a professional trumpet player and the sound carefully assessed by attentive listeners. He concluded, " What a difference in the tone quality! The most brilliant tone was given by the trumpet of brass 0.85 mm thick. The tone of the trumpet of lead was heavy and dull, while the tone of the paper trumpets was papery and excited general laughter. "[1]

Blaikley's demonstration involving, " a straight horn, or bugle, of metal; another one of exactly the same proportions, made of brown paper; and a third of metal of somewhat different proportions, in fact more like a cornet or bugle, " conflicts with this latter opinion. He

[1] Miller (86) 168

states, " you find it very difficult, or even impossible, to distinguish between the metal bugle and the paper one, but the slight difference in form between the two metal horns causes unmistakable difference in quality."[1] Thus two similar experiments produced apparently opposite conclusions about the role of material in the production of sound quality.

Another similar experiment by Victor C. Mahillon of Brussels, head of the celebrated musical instrument company and curator of the museum of instruments of the Belgian Royal Conservatory of Music, involving a cavalry trumpet made wholly of wood, led him to conclude that, " It gives exactly the same brilliancy as the instrument of brass, so that it is impossible to distinguish the one from the other. "[2]

The essence of the controversy seems to come from the opinion held by Mahillon and others of his persuasion, that, " the sonorous body is the column of air contained inside the tube, whose metal, wood or other material, has no office except that of determining the form and dimensions of the mass of air imprisioned within it, which is itself and itself alone, the vibrating body. "[3] Boehm and his followers held that the column of air could be to some extent modified by the material as well as the geometrical shape of the tube.

Miller, writing on flute tone in 1909, stated that the influence of wall thickness and the condition of the inner surface were well known but he concluded that it was conceivable that, " the presence or absence of a ferrule or of some support for a key might cause the appearance or disappearance of a partial tone. "[4] The effect of loading organ pipes has however been shown to have very little measureable effect on its tone. (cf. section 2.2.2) Miller continues, " The traditional influences of the different metals on the flute are consistent with the experimental results obtained from the organ pipe. Brass and German silver are usually too hard, brittle and stiff as to be little influence on the air column, and the tone is said to be hard and trumpet-like. Silver is heavier and softer, and adds to the mellowness of the tone. The much greater softness and density of gold adds still more to the soft-massiveness of the walls ... permitting a greater influence of the walls upon the tone, and increasing the richness of tone by augmenting the fullness of the partials, as is the case with the organ pipe.

[1] Blaikley (13)

[2] Miller (85)

[3] Lavignac (66)

[4] Miller (85) 170

However, as an example of what is apparently the opposite point of view, Coltman's statistical analysis of the judgements of listeners and flautists - who were allowed to play the keyless flutes made from silver, copper and wood - concluded, "[1]

" No evidence has been found that experienced listeners or trained players can distinguish between flutes of like mouthpiece material whose only difference is the nature and thickness of the wall material of the body, even when the variations in the material and thickness are very marked.... Moreover, the results suggest that even careful attempts to produce identical sounds on the same instrument produce variations that are more perceptible than any that might be associated with the material. "

One is led to surmise, if trying to reconcile these two standpoints, that Miller's conclusions about the relative merits of the metals favoured by flute manufacturers and players, may be due to the associated modification of the tone brought about by the presence of the keywork and not to acoustical advantages claimed for tubes made from particular materials.

Parker's experiments in which metal and wood clarinets were carefully compared, found that wall material was, among other factors, an important influence on tone. Backus' work on the relative importance of sound radiation from a clarinet's body and end, concluded thus,[2]

" although the walls of a woodwind instrument do vibrate when the instrument is sounded, these vibrations are insufficient to effect the steady-state tone quality either by radiating sound themselves or by altering the form of the internal air-column vibration."

He found that the sound pressure level radiated from the open end was 48 to 49 dB above that radiated from the body and was therefore negligible. He also points out that the vibrations in the clarinet body are due to the reed beating against the mouthpiece and not to radial vibrations due to the internal standing wave within the tube.[3]

Earlier, Knauss and Yeager[4] had studied the vibration of the walls of a cornet and showed that the walls of this instrument also were unlikely to radiate sufficient sound to affect the quality of sound. They also, using putty, attempted to dampen the wall vibrations and found that vibration was reduced when the substance was affixed

[1] Coltman (26) 523

[2] Backus (2) 1887

[3] Ibid 1883

[4] Knauss & Yeager (63)

inside the bell but, " the sound of the instrument was far from 'dead'. " The presence of putty outside the bell made very little difference to the sound.

2.3.2 Organ Pipes

From the number of studies about organ pipes among the literature reviewed, it would be reasonable to assume that the role of a material in sound production should be well understood. In fact, whilst organ pipe making practice has been questioned, discussed and experimented upon, many studies do not present corroborating material and overall understanding of the subject is still largely abstract or conjectural. The subject has four principal facets. Experiments involving pipes made in various materials are of course directly relevant, but studies of organ pipe mechanism, wall vibrations and the extent that voicing alters the tone quality also contribute in important ways to understanding.

Fundamental to studies of the importance of materials on tone quality is the question whether the instrument as a whole contributes to the tone, or if the instrument serves only to imprison a peculiarly shaped air column which, when brought to resonance, produces the characteristic sound. Our knowledge of the mechanism of the organ pipe is incomplete, and will develop only as understanding of the motion of vibrating air in a tube and the jet drive mechanism is gained. Much work has still to be done on the coupling of pipe and jet. First explanations of the motion of air in a tube were put forward in 1826 by Weber[1] and in 1840 Cavillé-Coll introduced the concept of the air reed which was developed by Helmholtz, Schaik and Wachsmuth.[2] The latter's experiments represent an important advance in the formulation of the 'edge tone' theory principally associated with Kárman.[3] Neither his 'vortex street' theory or the simpler 'air reed' theory were satisfactory and other experimenters, notably Brown, but also Nyborg, Burkhard and Schilling, examined the jet more closely. Brown's[4] nebulous qualitative theory which he called 'wake formation' (a compression-rarefaction effect which travelled backward from the edge causing the formation of vortices) showed that edge-tone production is not a simple phenomenon but a complex effect involving both air reed and vortex formation. A physical model for the mechanism of edge-tone production was developed

[1] Weber (18)

[2] Mercer (80) 379-80

[3] Norman (90) 30

[4] Brown (18) 493

in the early 1960's by Powell[1] in which he showed that the fluctuating lift force at the edge, caused by the impinging jet, sustained the oscillations. He proposed also that a similar mechanism may be responsible for the domination of the resonator as the principal factor in the pipe mechanism. The coupling between resonator and edge-tones is the most complex of the three features of the mechanism. The damping of high partials associated with pipes of large scale eliminates harmonics which would otherwise be out of tune due to the effect of the well known end-correction phenonenon. Thus,[2] although the harmonic structure associated with a simple cylindrical resonator is not precisely harmonic, organ pipes produce tones which are more accurately integer multiples of the fundamental.[3]

Powell's feedback notion was developed by Cremer, Ising and Bechert. The 1968 Cremer-Ising[4] theory accounted qualitively for this distinctive feature of organ pipe oscillation, the association of blown frequency and pipe modes, and other features too, such as the tendency of the fundamental pipe frequency to vary with blowing pressure. Coltman's work, approaching the subject from a slightly different stance, produced a second explanation of the coupling mechanism involving the formation of an oscillatory pressure gradient due to the incompressible forces associated with its own decay. This, and the Cremer-Ising theory, were comprehended by a more general approach initiated by Elder.[5] In his paper of 1972, " the action of the air jet on the air in the pipe is almost completely explained " wrote Fletcher,[6] who extended Elder's work and, using the approach for the calculation of harmonic development initiated by Benade and Gans,[7] predicted the behaviour of several harmonics of a pipe which agree well with observations. This paper[8] also highlights the shortcomings of the present theory about the accoustically disturbed jet.

Theoretical studies of the mechanism of organ pipes, whilst facilitating an understanding of the observable traits of the pipe and

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[1] Powell (98)

[2] Norman (90) 27

[3] Boner & Newman (15)

[4] Cremer-Ising (29)

[5] Elder (36)

[6] Fletcher (40)

[7] Benade & Gans (12)

[8] Fletcher (41)

including among the variables for which good predictions of the effect on tone can be made, several of which are regarded highly by organ pipe voicers such as mouth width and cut up, have not yet refined a conceptual model in which the properties of materials can be evaluated according to their effect on tone. It would seem that this area will continue to be neglected until the jet-pipe interaction is understood more fully.

The effect on tone due to the vibrations of the pipe body and the radiation of sound through the walls has been studied to ascertain the extent that the damping qualities associated with the wall material effects the tone quality. A. H. Jones[1] concludes that wall material has little effect so long as the walls are hard, smooth and fairly rigid. He explains that only if the walls are thin and flexible does the material become important, influencing both pitch and quality. This is borne out by the very early investigators such as Savart (1825) and Liskovious (1842) who found that the pitch of a pipe made from parchment could be lowered by impregnating the material with water vapour.

Lottermoser[2] however, suggested that organ pipe timbre is effected by periodic modulation of certain formants whose frequencies lie near weakly damped resonance modes of the tube. These modes are excited by the column of air but are dependent on the nature of the material from which the tube is constructed. Jones[1] and Boner and Newman[3] refute this theory. They point out that the modulating frequencies necessary to produce the lines found in his spectra are far lower than any modes of the pipe wall.

Extending their work on clarinets to organ pipes, Backus and Hundsley conclude that,[4]

" the wall vibrations in organ pipes as commonly constructed have negligible influence on the steady pipe tone, and probably little on the transient buildup as well. " Barely detectable effects were found in very few pipes; if important, vibration effects should be seen predominently in most pipes. The tone structure of a pipe is determined by its geometry, and the importance of this factor is demonstrated by one experiment in which it was found that lining the inside of the tin pipe at its open end with paper and thus reducing its diameter by a few mils over a distance of a few inches, the level of the 4th harmonic of the pipe tone was reduced 15 dB. "

[1] Jones (57)

[2] Lottermoser (70)

[3] Boner & Newman (15)

[4] Backus & Hundley (3) 944

The authors, by comparing the acceleration levels of the wall vibrations when the pipe was speaking normally with those measured when it was driven by vibrating the upper lip, were able to assert that wall vibrations are produced by the air stream from the flue striking the lip. Further analysis of the harmonic spectrum showed that, " these vibrations produce a negligible SPL as compared to that radiated by the vibrating air column of the pipe. "

Helmoltz[1] attempted to explain the tonal difference between pipes made in different materials by the effect of friction. Other writers, though agreeing with his observations about the range of harmonic development possible, do not attribute the phenomenon as Helmholtz did. In Barnes'[2] opinion, " the thickness of the metal has much to do with the development of harmonics, or the reverse. Thick metal causes the tone of pipes made with it to be more foundational. Pipes made with thin walls have greater harmonic development. " Glatter-Götz[3] however, found that, " the variation in harmonic structure among pipes of different materials was the same as the variation among pipes of the same material, " and concluded that the only important factor affecting pipe tone is the resonator's shape.

Lottermoser[4] disagreed with this, reasoning that it was impossible that organ builders could have deceived themselves for so long, but his experiments on four pipes made with interchangable resonators from lead, zinc, tin and copper, reveal that although differences in harmonic structure were apparent, the spectrum also varied with the position of the microphone. He found that the spectrum of a tin pipe could be changed into that of a zinc pipe simply by observing it from a different position. Catagorical asertions about the quality of tone radiated by tin pipes should, on the basis of this information, not be made even by organ builders.

Although his hypothesis already mentioned, that organ tone is influenced by the intermodulation between the standing wave and the modes excited within the tube, had been seriously questioned, in 1962 Lottermoser[5] produced a further report in which he set out to justify from an acoustical standpoint the use of lead and tin alloys in preference to zinc. From the spectral analysis of six similar pipes

[1] Helmholtz (50) 94

[2] Barnes (5)

[3] Glatter-Gotz (46) 99

[4] Lottermoser (69)

[5] Lottermoser & Meyer (72)

made in two types of zinc, copper, pipe-wood and two types of tin/lead alloy, he again concluded that distinctive effects are related to particular pipe materials. He does not however, show that identical spectra can be produced from pipes made of similar materials, nor is there any indication other than an acknowledgment of an organ builders' assistance, that precautions were taken to assure similar voicing of all six pipes.

In a similar experiment conducted by Harrison and Harrison of Durham,[1] in which organ pipes were constructed in different alloys of tin and lead, results showed that after skilful voicing there were characteristic differences in tone. A latter paper by Lottermoser,[2] describing experiments on plastic organ pipes is open to similar criticism. In a further statement from this paper, he asserts, from the musical standpoint that, organ pipes should radiate harmonic sounds uniformly in all directions. But since the directional characteristic inherent in the mechanism due to the orientation of the mouth is valuable in enabling organ pipes to speak correctly into buildings as are rarely, if ever located where they can be perceived from every direction, it is doubtful that a pipe could better fulfil its musical role if it did radiate sound uniformily.

In similar experiments to those carried out by Lottermoser, Boner and Newman[3] found that cylinders made from various metals as well as wood, and one of a single layer of wrapping paper, produced differences in harmonic spectra which, with the exception of the paper one, show that material has very little effect on the steady state spectrum of the pipe. They also found that listening tests showed very small audible differences.

A number of useful studies have qualitively discovered the effects of the half dozen or so adjustments associated with voicing organ pipes.[4] None of the studies is as recent or complete as that of Nolle.[5] In this he compares the sounds from experimental pipes fitted with micrometer adjustment of mouth height and width as well as flue width and languid thickness, with the theoretical predictions of others, particularly Coltman.[6] Thus, tonal changes produced by certain voicing changes are

[1] Richardson (102) 212

[2] Lottermoser (73)

[3] Boner & Newman (15)

[4] See ref. 3 page 7

[5] Nolle (88)

[6] Coltman (27)

quite well known. However, the relative effect in comparison with that contributed by the wall material has not been studied, though McNeil[1] suggests that metal percentages are less important than other facets, including voicing changes, in establishing the tone of a pipe. E. G. Richardson was more emphatic stating that,[2] " the effect of material on the quality of organ-pipes seems to be less important than some organ builders suppose, for the actions of the voicer can mask any special effect of the material. "

Finally, an interesting remark, unfortunately unsubstantiated, from the paper by Ingerslev and Frobenius:[3] " It is likely that the material used at the mouth, especially for the languid and upper lip, has more influence on the quality of the sound than the material of the pipe body. "

1 McNeil (77) 10 2 Richardson (102) 216

3 Ingerslev & Frobenius (55) 18

2.4 Organ Building and Instrument Making Practice

Material is but one aspect considered when designing the pipe work for a new instrument. Detailed information is required about the size and shape of the pipes, the physical position of pipes in the instrument and the wind pressure on which they will stand. Considerations also include the balancing of the various divisions or 'werks' of the organ and the acoustics of the building is to be set. The designer must supply information about the stops' speaking length, the circumference, mouth-width and the height it is to be cut up, the wind pressure on which it is to stand, as well as the material in which it is to be made and its thickness. The methods of working and established practice of organ builders provides an important insight into the subject of material and tone.

A general rule is applied for selecting the alloy of lead and tin. Flute tone stops are made in 30 per cent tin, hybrids in 45 per cent, reeds in 60 per cent and both diapasons and mixtures in 70 per cent tin. Lead is a material possessing very good damping qualities. It is therefore notable that this dominates the alloy used for duller toned stops and tin predominates for bright toned ones. It is common practice that metal rich in lead is used thicker than that consisting mainly of tin.

The above tends to suggest that lead is used for certain organ stops where a less developed tonal spectrum is desired and that its sound absorbing qualities contribute to the instrument's sound. Stops for brighter tones, because they are fabricated in a less absorbent material, propagate richer tone by the same reasoning. Whether or not this is true, it is clear from a structural point of view that the alloy rich in tin is stronger than the other and for this reason if non-other, can be used thinner than the softer, predominantly lead alloy.

The physical characteristics of stops, also effect their tone. Those which use alloys rich in lead usually have greatest cross-sectional area (widest scale), but the foundation pipes' diameters are considerably less. This factor is paramount in deciding the tone of a pipe but once again it is almost impossible to assess the relative importance of this parameter compared to the materials' influence.

One other parameter linked with this is the height of the mouth, referred to as the mouth cut-up. Flute toned pipes are provided with high mouths, low cut-up being associated with rich tone and therefore utilised in diapason stops. This characteristic may be of some importance since the sound from an organ pipe is radiated principally from the mouth and open end, very little sound emerging through the pipe body. Wide scaled pipes therefore have a larger area from which the sound may disseminate, not only at the open end but also at the mouth.

Organ pipes are made in a soft malleable metal. The geometrical shape of the resonator is critical to the tone of the pipe and in the case of a cylindrical pipe with parallel sides, slight distortion from the round section can profoundly effect the tone. The nature of the material used and the large amount of handling the pipes are subjected to both in the factory where they are assembled as blanks, voiced, and packed ready for transportation to the site of the instrument, as well as when being 'planted' on the windchest, tuned and finally 'finished' in situ, make it unlikely that pipes will maintain real accuracy. Indeed, a pipe which speaks badly may be distorted slightly by the voicer to correct this fault. Such inaccuracies in the shape of the resonator provide one further possible variable affecting the tone of particular pipes.

For economic and structural reasons large pipes are often made in zinc, and aesthetic considerations sometimes lead to the production of pipes in copper. Such pipes are, however, fitted with mouth parts (languid, upper and lower lips) made from pipe metal. In the case of zinc, the resilient property of the metal would justify the manufacture of these parts which must be malleable, in a more suitable material. However, the use of pipe metal mouth parts in copper pipes tends to suggest that the material from which these are made can exert an influence on tone. Mercer,[1] admits that little is known about the vibrations of pipe upper lips, but asserts that zinc upper lips produce a keener tone than plain metal.

One further observation completes this comment on the methods adopted by organ builders today, relying on the traditions of their forebears. The textured surface produced in the casting process on the underside of the metal by the linen covering of the casting table is often found on the inside of the pipe resonator. This surface could conceivably effect the standing wave in the resonator by contributing to

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1 Mercer(79)

the boundary layer of zero particle motion causing a change in both the velocity of the wave and the absorption of the tube.

2.5 Discussion and Evaluation of Aspects which Require Further Study

2.5.1 Introduction

The study of the influence that material has on wind instruments has a long history in which corroborating and conflicting information has been presented, prejudiced judgements have been made, and the attitudes of instrument-makers and performers have been questioned, upheld and rejected. From the review of literature presented above and the information from previous sections about pipe making design and practice, a number of areas which appear to require consideration or further study have been identified. Some relate to the acoustics of pipes, further knowledge of which will extend understanding of the connection between tone quality and pipe wall materials. Others involve aspects of sound analysis and experimental technique, which it is essential to resolve before experimental work can be undertaken.

2.5.2 Lack of Unanimity in the Results of Steady State Experiments

The opinions of experimenters using steady state techniques to analyse the tones of organ pipes made in different materials are varied and apparently repudiate one another. Laying aside for consideration in section 3.1.3 the differences in manipulation of the pipes, and sighting for example the work of Lottermoser[1] and Boner and Newman,[2] (cf section 2.2.2) the former defends the use of traditional materials but the latter reports little difference in the sounds of pipes made in different materials. Similarly, the result of an experiment by Harrison and Harrison of Durham[3] apparently confirms Lottermoser's findings.

There are two important points here. First, we note that the amplitude changes found by all these researchers are small compared with the levels of many of the components identified, and that none of experimentors show that repetitive analysis of the same signal will produce results which are quite similar. The continuous perturbation of almost any musical signal even in the steady period, makes it unlikely

[1] Lottermoser (70)

[2] Boner and Newman (15)

[3] Richardson (102)

that subsequent analysis, unless averaged over a very considerable number of samples, would reveal precisely the same amplitudes for each component. Secondly, the researchers all used pipes about 2 feet in length. Clearly, the assumption that other pipes will behave like this one, which is implied in Lottermoser's and Boner and Newman's work, is unseemly. Experiments should involve a wider range of pipe length, if not also a range of pipe tones.

Clarification of the results obtainable by steady state analysis is therefore required - see section 4.2. The extent to which a particular sound differs from another is however, related not to the range of amplitude readings obtained, but to the sensitivity of the human ear - see section 3.2.2.1

2.5.3 Voicing Adjustments

The voicing of organ pipes is held the most skilled and artistic aspect of organ-building. "It is a tribute to his (organ-builders) experience and ear training that he is able to assess so quickly and accurately the effects of the adjustments that he makes".[1] The preliminary voicing and subsequently the 'finishing' of the pipes once positioned on the windchests, determines the musical value and effectiveness of the instrument: the quality of tone. Although he works on each pipe individually, the voicer's aim is to produce homogeneity within a rank of pipes, and stops which will combine with others to form effective chorus and hybrid sounds.

Neither the musical literature or the study of pipe making reveal much about how voicing influences tone, although the changes associated with particular adjustments are fairly well documented in the scientific studies reviewed. The adjustments in question are:[2]

(1) the size of the foot hole.
(2) the rounding of the edge of the bore
(3) Nicking = small cuts in the languid or lower lip
(4) the width of the flue
(5) the positioning of harmonic bridges
(6) the height of the languid
(7) the height of the mouth cut-up
(8) the lateral setting of the upper lip
(9) the sharpness of the upper lip
(10) the addition of a compensator amplifier

Nolle's[1] (1979) study is the most recent and complete summary of the effects of these adjustments for circular metal pipes. Although this provides conclusions about the effect of the various adjustments, a more quantative evaluation of the audible effects of the various voicing adjustments compared with the effect of materials seems important for this study. Apart from that alternative materials put forward can only be acceptable to organ builders if they can obtain the sounds they wish from pipes fabricated in it, it is possible that slight differences in tone could be corrected by competent voicing. The artist-craftsman's awareness of the effects of these adjustments is difficult to assess quantitively and therefore the viability of improving sounds radically by these adjustments can only be ascertained by experiment. The dearth of knowledge in this area is understandable for, as with the isolation of the resonators' role in pipe tone, study is exceptionaly difficult due to the interrelation of variables and the subjectivity of defining 'tone quality'.

Of primary importance is the extent of the tonal changes effected by voicing adjustments and, since this work was framed in the light of the preliminary experiments on materials for the resonator, the extent of changes will be assessed by comparison with the changes occurring in those experiments. Three aspects of voicing are considered here, firstly, the effect of voicing adjustments on pipe tone, secondly, the viability of voicing pipes geometrically similar to produce homologous sounds irrespective of the material from which they are fabricated, and thirdly, the effect of adjustments to the pressure transient.

It is certain that pipe tone can be modified by the voicer, but what is not known, and is of interest in this work, is whether the range of tone possible could compensate for the loss of tone colour associated with the characteristics of material, if the pipes were made in non-standard materials. Of course, this parameter of tonal modification is interrelated with the other factors influencing pipe tone: pipe geometry and the possible effects of material and wall thickness.

2.5.4 Wall Thickness

2.5.4.1. Physical Attributes

The lack of comment on wall thickness in the experimental work

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[1] Nolle (38)

reviewed is notable, though the choice of wall thickness is specified carefully by the organ builder and the graduation of thickness throughout the pipes of stops is not arbitrarily decided upon. The survey of pipe making practice also shows that pipes made of alloys rich in tin have thinner walls than pipes made from predominantly lead alloys. The reason for this may be structural, but the selection of combinations of particular materials and specific scales of wall thickness suggests that the two are integrally related. Since thick walled pipes are used in foundational tone stops and thin metal is used for bright toned stops, could wall thickness be more important than material in the tone quality produced: would it be possible to produce diapason tone from a 30 per cent tin pipe of diapason scale if the walls were much thinner than is usual for this alloy? Conversely, could flute tone be elicited from pipes of 70 per cent tin which have appropriately thicker walls?

This notion about the importance of wall thickness is given weight by the apparent antithesis between the findings of Miller[1] and those of Glatter-Götz.[2] Miller attributes flute tone colour to the elastic qualities of the metal, but Glatter-Gotz' experiments on organ pipes show that the variation in harmonic tone structure among pipes of different materials was the same as the variation among pipes of the same material. He concluded that the only important factor affecting pipe tone is the resonator's shape. Since the organ pipes were relatively thick walled compared with 0.2 mm or 0.3 mm for the tubes of Miller's flutes, the tone of the organ pipes would be affected proportionately less by the changes of material or thickness than the flutes. Changes, therefore, of material or thickness in the thin walled instrument are probably more noticeable than in the thick walled organ pipes, though they may also be associated with the position and weight of keywork or the players grip on the instrument.

Coltman's[3] demonstration with three flutes also bears out this notion. The silver and wood tubes were of the same quality and thickness as those used in flute manufacture and the other, a copper tube, was much thicker than either of the others. It is interesting to speculate whether differences would become apparent if all three tubes had walls of the same thickness.

Tests regarding the effect on the harmonic spectra of organ pipes of

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[1] Miller (86)

[2] Glatter-Gotz (46)

[3] Coltman (25)

increasing the rigidity of organ pipe walls carried out by Backus and Hundley,[1] first by surrounding the pipes with a larger tube sealed to the organ pipe and filled with water, and secondly, by grasping speaking pipes and monitoring any change in spectrum, also reveal the experimenter's lack of concern for the influence of wall thickness, since the two tubes tested were a 'tin' organ pipe resonator of standard construction and a copper pipe with walls 10 mil thick.

Another possibility suggested by the poor response characteristics which Wogram[2] found in thin walled brass instrument bells, is that there is a minimum thickness below which tone is very significently affected by wall vibration. This condition is sometimes encountered by organ builders who may deform the cylindrical shape of the resonator, solder a small bar through the pipe, or fit it with a strengthening collar in order to give the pipe more structural strength.

These observations suggest that work should be done to assess the importance of wall thickness perhaps with the view of demonstrating a critical thickness for pipes made from particular materials sounding notes of specific frequencies below which thickness a particular material will contribute peculiarly to the tone. These conjectural ideas are given theoretical weight by the following discussion of sound radiation through the pipe walls.

2.5.4.2. Theoretical Links

Backus and Hundley's study of the effect of non-rigid walls on pipe tone[3] provides a theory which enable the calculation of sound radiation levels produced by frequency changes induced by the elasticity of the cylinder walls. The theory is applied to certain pipes and the results compared with experimental findings involving the artificial vibration of pipes. They conclude that pipe tone quality, at least for cylindrical pipes, is determined by its geometry; that the vibrations of the pipe wall are unimportant, influencing imperceivably the standing wave and the radiation of sound, and therefore that pipe wall material has no effect on the tone.

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[1] Backus and Hundley (3)

[2] Wogram (129)

[3] Backus and Hundley (3)

The theory they present does however, provide a means of associating the details of a pipe's geometry, known as its scaling, with the wall thickness and the elastic properties of the wall material. This enable a study of the effect of wall material, on pipes of different tone quality and also facilitates investigation of the material's thickness. The theory is applied to pipes of various sizes and the calculations evaluated against experimental work to ascertain its validity. It is then applied to various situations to calculate the wall thickness required for pipes made in alternative materials.

2.6 Summary

Scientific research and debate about materials and musical tone quality has produced no clear explanation of the role materials play in the tonal structure of instruments. This survey shows a range of dissenting opinions not only from those who have studied organ tone, but from researchers who have concerned themselves with woodwind and brass instruments also. Though it is true that the prejudices of players and musicians have frustrated serious attempts to resolve the questions, the opinions of those who listen to musical sounds provides an acid test for resolving the controversy. Instrument makers, having absorbed a wealth of empirical knowledge from generations of craftsmen before them, can make contributions to the debate which should not be regarded disparagingly in the light of experimental results. It is intended that empirical and scientific ideas should be considered along side in this work, to stimulate debate and resolve the question.

Six areas for further study have been identified:

(1) Experiments should be carried out to clarify the tonal modifications discernible by steady state analysis of organ pipes made in dissimilar materials.

(2) Analysis of the onset transient is required to understand more fully the effect of wall material on tone.

(3) Wall materials and wall thickness are related in their effect on tone and should be investigated to show the tonal modifications attributable to each.

(4) Voicing adjustments are known to effect the tone quality of organ pipes and may therefore provide a means of correcting slight differences in timbre resulting from alternative pipe fabrication materials. The extent of the tonal modifications possible by voicing should be assessed.

(5) Theoretical hypotheses which link pipe wall properties with pipe scales should be applied to the question of wall material effect on tone.

(6) Sound quality comparisons, the interpretation of physical analysis results, should be related to the discrimination of man's auditory ability particularly when the question is whether two sounds are so similar as to be indistiguishable.

The following section considers the analysis of sounds and experimental feasibility, whilst Section 4 discusses the experimental work undertaken and documents the results.

Chapter 3.

BASIC EXPERIMENTAL TECHNIQUES

3.1 Introduction

The previous section identifies a number of areasfor experimental work. The techniques for this must be considered before practical study can be undertaken. In this chapter experimental methods for studying organ pipe materials are discussed - Section 3.3 - and also the analysis of signals which constitute the sounds under scrutiny here. - Section 3.1

3.2 Analysis of Musical Sounds

3.2.1 The Nature of Organ Sound

Musical sounds, despite their apparent peridicity, are essentially evolutive and rarely if ever attain the steady condition since they normally involve a continuous attack and decay. Percussive instruments such as the piano and harpsichord are obvious examples of this, though even instruments capable of sustaining sounds are rarely required to do so during a piece of music. Long notes, when they are required, are usually modulated by the articulate bowing or tonguing of the player. In the case of the organ, where sustained notes are feasible, the sound is continuously modulated by the inherent instability of the acoustic mechanism of the pipe. In normal playing, bearing in mind the speed at which notes are changed and the low damping of the resonator, the transients' duration may contribute to the total duration of a particular note. An analysis of a non-percussive musical sound in the time domain will involve a period during which the sound is developing, a period of relative steadiness, and a well defined period of decay. The steady period can be analysed using spectrum analysers to reveal the amplitude of each of the frequency components which combine to form the sound. Steady state spectra are usually presented as graphs such as that in figure 3.6 which shows the fundamental and five other frequency partials. The partials, because they are in harmonic relationship, are referred to as harmonics, though non-harmonic partials sometimes occur in the steady state analysis presented in this study, i.e. figure 3.7 In figure 3.6 the fundamental (harmonic 1) has an amplitude of almost 69 dB, the 2nd of 24 dB, the 3rd of 42 dB and the 4th of 24 dB. Harmonics 5 and 6 are barely detected and have amplitudes below 20 dB.

The onset is not simply the gradual buildup of the steady-state spectrum: it may include brief entries of partials which are not present in the steady-state, partials which constitute the steady structure but at various amplitudes, and sounds which are quite irregular and which can not be considered modifications of the steady periodic wave such as noises arising from the wind entering the instrument and rushing across the mouth parts.

It is clear from various physiological reports which demonstrate that even musically trained listeners are unable to identify sounds devoid of their familiar onset transient, that the transient has an important role in our subjective impression of sounds.[1] Saldantia and Corso[2] show that in listening tests involving the tones from ten instruments, those which presented initial transients and a steady state were best identified. They show too that the decay transient is of limited value since identification was not improved when this was presented.

3.2.2 Perceptual Evaluation

3.2.2.1 The Relevance of Physiological Considerations

> ' Rightness and Wrongness are possible in regard to perception, and to perceive is to judge. While it is possible to judge rightly or wrongly, then in regard to perception as well, rightness and wrongness must be possible. '
>
> Aristotle: Topica 11.

This is a study of musical sound, our perception of which depends wholly upon the analysis performed by our auditory faculties. The brain is able to differentiate sounds in a babble and a trained listener can choose to listen to the overall sound of, for instance, an orchestra, or allow his attention to focus on some particular instrument in the ensemble. The reality of this facility leads to the supposition that the ear can selectively detect the characteristic tonal qualities radiated by a particular instrument. Various experiments have shown that the ear is capable of some form of frequency analysis,[3] but the analysis performed by our sensory organs is in important ways dissimilar to the analysis performed by electronic transform equipment. It is therefore vital for a study of musical sound and for the interpretation of the

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[1] Clark (24)

[2] Saldantia and Corso (106)

[3] Littler (68) 173

results of electronic analysis, that the peculiarities of the human system are noted and the way they affect the analysed results considered before conclusions are drawn. For example, physical analysis may show two sounds to be dissimilar due to differences in the amplitudes of certain harmonics. If however, those differences in level are in the range within which the ear can not discriminate, the sounds will appear identical to the listener. When studying musical phenomena it is this which is most important, not the description of physical analysis. The converse may however, be true in certain instances. The auditory mechanism is extremely sensitive in certain regions and may often detect dissimilarities which may not be easily observed in physical analysis.

A musician's impression of the sounds he hears is likely to be communicated in subjective phrases concerning pitch, loudness, timbre, density, brightness, roughness, duration, rhythm and fullness, but these are not psychologically independent of each other and are at best vaguely defined.[1] Even timbre, the term understood as having essentially musical significance, particularly for differentiating between sound qualities, embraces many individually perceivable acoustical qualities which are associated with the physical characterisation of the sound.

3.2.2.2 Human Auditory Sensitivity

Clearly, all the information about sounds upon which our impressions are based, is present in the waveform received by the ear. Due to the limitations of man's auditory ability, slight changes in tone can take place unnoticed and therefore, the analysis performed by our sensory organs is not entirely similar to that performed by electronic analysers.[2] Knowledge of the extent to which differences in tone quality are perceived by the listener enables a realistic, rather than a theoretical assessment of similarity to be made. This is more appropriate for a study of musical sounds since they are normally identified only by the impressions gained by hearing.

The factors affecting the perception of musical sounds by human hearing which are discussed in this section are:-

(1) The relative insensitivity of the cochlea to high harmonics and the individual perception of low harmonics.

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[1] Wedin and Goude (123) 228

[2] Weyer (126) 234

(2) The intergration time required for the ear to respond to changes in the stimulus due to the mechanical nature of the ear.

(3) The extent of the ear's sensitivity to the amplitude of partials and to changes in their amplitude.

(4) The extent of the ear's sensitivity to the presence or absence of partials and slight changes in their frequency.

(5) The masking effects of large amplitude partials.

Analysis is performed only on lower frequency components in terms of frequency and amplitude corresponding with the individual frequencies of the Fourier transform.[1] The frequency range in which the ear is able to perform this analysis is known as the Formant region. Each of the harmonics of a sound which lie in the formant range excite individual hair receptors in the cochlea but the higher frequencies fall within the bandwidth of a particular receptor due to the narrowing of the frequencies between progressively higher partials.[2] Analysis in terms of amplitude and frequency of more than one tone by a single receptor is impossible, therefore, the higher components in the spectra are perceived collectively as a single component, a sharp tone quality called Residue.[3] As an example of this in practice, the first nine harmonics of a tone having a 200 Hz fundamental are perceived as individual frequencies. This is because the critical bandwidth of the basilar membrane for a 1800 Hz sound, the ninth harmonic of a 200 Hz signal, is about 180 Hz, but at 2000 Hz, the tenth harmonic of a 200 Hz signal, the bandwidth is over 200 Hz, making it impossible for the tenth and subsequent harmonics to be perceived individually. The importance of individual non-formant components is probably minimal.[4] Winkel[5] suggests that the ear is particularly insensitive to changes in the amplitudes of such overtones, to the extent that only a highly trained ear would notice, the entire erasing of one. Figure 3.1 has been drawn using the detail of Plomps' work and shows the number of harmonics which should be individually perceived at frequencies over the auditory range.

As has already been shown, the frequency components of a sound and their amplitudes are important physical characteristics. Sound must be perceived over a period of time, therefore, any changes in frequency spectrum, either in terms of the amplitude or the frequency of the partials, will contribute to the overall effect of the sound. The sounds

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[1] Schouten (109) 991

[2] Meyer (126) 236

[3] Schouten (109) 992

[4] Plomp (95) 1636

[5] Winkel (128) 112

are analysed by the ear, which because it is a mechanical device, requires time to respond to the sounds presented to it. The minimum period required for the ear to respond is conditional on the energy of the signal, its frequency, length and steadyness. This can take as little as 10 mS for high frequencies followed by a period of silence, but for low frequencies 50 mS is common. For most musical sounds this period is not important since for continuous sounds the ear integrates fluctuations over approximately 50 mS intervals.[1] This combined with 30 mS, the time approximately the ear requires to establish formants from a group of harmonics,[2] produces a tone colour recognition time of about 60 mS.

Since even abrupt onsets are not immediately perceived at full strength, the recognition time for a particular tone could be even longer, since for a pp tone the amplitude is not perceived for 65 mS, and for a ff sound 140 mS is required.[3] Thus, musical transients are not analysed period by period in the ear. The sound is perceived as part of a complex auditory smear.

Various physiological studies have been carried out about the role of phase in defining the quality of a sound by a human listener. These are discussed in Appendix A. It is clear from these reports that this factor is of little or no importance to the perception of musical sounds.

To what extent then does the auditory mechanism perceive the a-periodicity of the quasi-periodic sounds of the steady period, and the frequency and amplitude fluctuations of the transient? It appears from the work done on the stability of notes during musical performances, their modification by vibrato, mistunings and intonation,[4] that small pitch fluctuations of this type are either ignored or restructured by the listener. It is therefore, reasonable to assume that similar minor changes in frequency among harmonic components may be similarly ignored.

Wiñkel[5] states that the amplitudes and frequencies of individual partials can be changed before a distortion in the tone colour is noticed, and Backus and Hundley[6] suppose that a 1 dB change in sound pressure level of an organ pipe is inaudible. More information is available on the minimum acceptable changes in amplitude than for changes of frequency. Fletcher[7] shows the minimum detectable changes for various

[1] Wiñkel (128) 53

[2] Joos (58) 9

[3] Wiñkel (128) 176

[4] Simmonds (110) 48

[5] Wiñkel (128) 115

[6] Backus and Hundley (3) 945

[7] Fletcher (38) 154

frequency and sensation levels. (see Fig. 3.3). For frequencies about 3000 Hz changes of 3 Hz may be detected. Above this frequency changes are less audible as frequency increases. These values however, are for single sounds: it is probable that in a complex sound the amplitude of a certain frequency component could fluctuate more than this and not be perceived.

Although the fundamental frequency of musical sounds falls within the frequency range of people with normal hearing, the perception of the partial structure is affected by the range of frequencies audible. The maximum frequency audible by some children can be as high as 25 K Hz, but for most adults is about 15 K Hz.[1] This figure is reduced by presbycusis in old age, usually to below 10 K Hz.[2] The ear is most sensitive to middle range frequencies - 1 K to 6 K Hz - where sounds below 0 dB[3] can be detected.

As well as frequencies, amplitudes of single partials can be changed greatly before a distortion in the sound colour is noticed.[4] A graph of minimum detectable changes in pressure levels at various frequencies is given in Fig. 3.4.

In the presence of high amplitude harmonics, the recognition of lower amplitude ones is often reduced or entirely masked. The threshold of masking below which sounds can not be heard is important for this work since changes in the level of a component which falls below this will have no perceivable effect on the sound of the pipe. A great deal of work has been done about this phenomenon,[5] which, like the minimum amplitude audible, is dependent on the frequency and amplitude of the fundamental. (Fig. 3.5). Although high frequency masking can effect tones of lower frequency, the masking effect on formant harmonics of the fundamental is of particular importance here. Masking in the presence of the fairly low frequency signals discussed is striking.[6] For example, an 80 dB fundamental at 200 Hz will mask its second, third and fourth harmonics unless their amplitudes are greater than 70 dB. This is an extreme case because as the fundamental frequency increases the forward masking decreases and masking is proportionally less for lower amplitude

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[1] Olson (92)
Kinsler (62)
Wood (130)

[2] Culver (30) 56

[3] re. 2×10^{-5} N/m^2

[4] Winkel (128) 115

[5] Kinsler and Frey (62)
Schouten (109
Small (111)
White (127)

[6] Littler (68) 135

signals. For a similar amplitude signal at 800 Hz, the second harmonic is detectable at 50 dB and the thid at 45 dB. Similarly, a 200 Hz fundamental at only 40 dB would mask a 400 Hz tone less than 23 dB and a 600 Hz tone less than 15 dB. It is important to stress that auditory physicist's experiments on masking the audibility of frequency at low amplitudes and the rate of perception, are carried out under conditions which are most favourable for the phenomena to be demonstrated and that they therefore represent more critical judgements than could be made by the most attentive listener at a concert where the acoustic properties of the environment, audience noises, and the music itself prohibit painstaking analysis of individual tones.

The graphs of masking effects, frequency and amplitude sensitivity, the threshold of hearing and the limitations of individual perception of harmonics (Figs. 3.1 to 3.5), show that at certain frequencies, changes in pipe tone parameters are more likely to be perceived than at other frequencies. The lowest threshold of hearing lies between about 1000 Hz and 4500 Hz and in this range most harmonics will be detected below the level of residue. For the amplitude levels and fundamental frequencies under discussion, the minimum detectable changes are fairly flat curves; the frequency becomes important only for very low amplitude signals. Frequency perturbations are only significant below about 5000 Hz. A range of maximum sensitivity can therefore be defined, approximately between c^2 and c^5, 500 Hz to 4000 Hz.

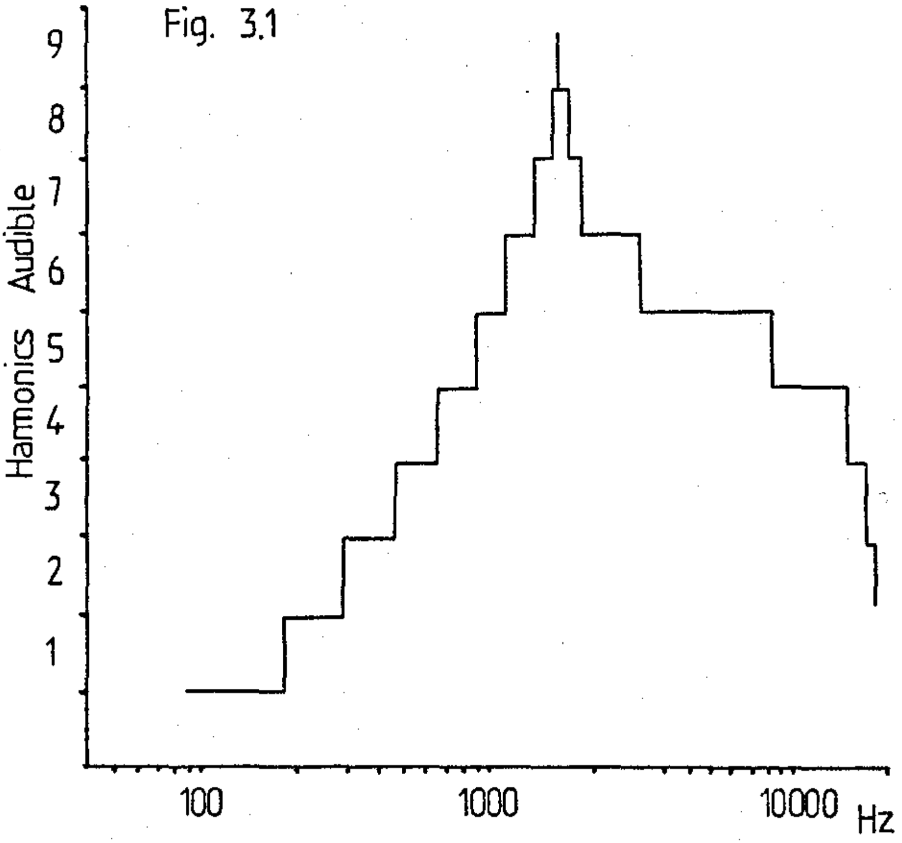


Fig. 3.1

Harmonics Individually Perceptible

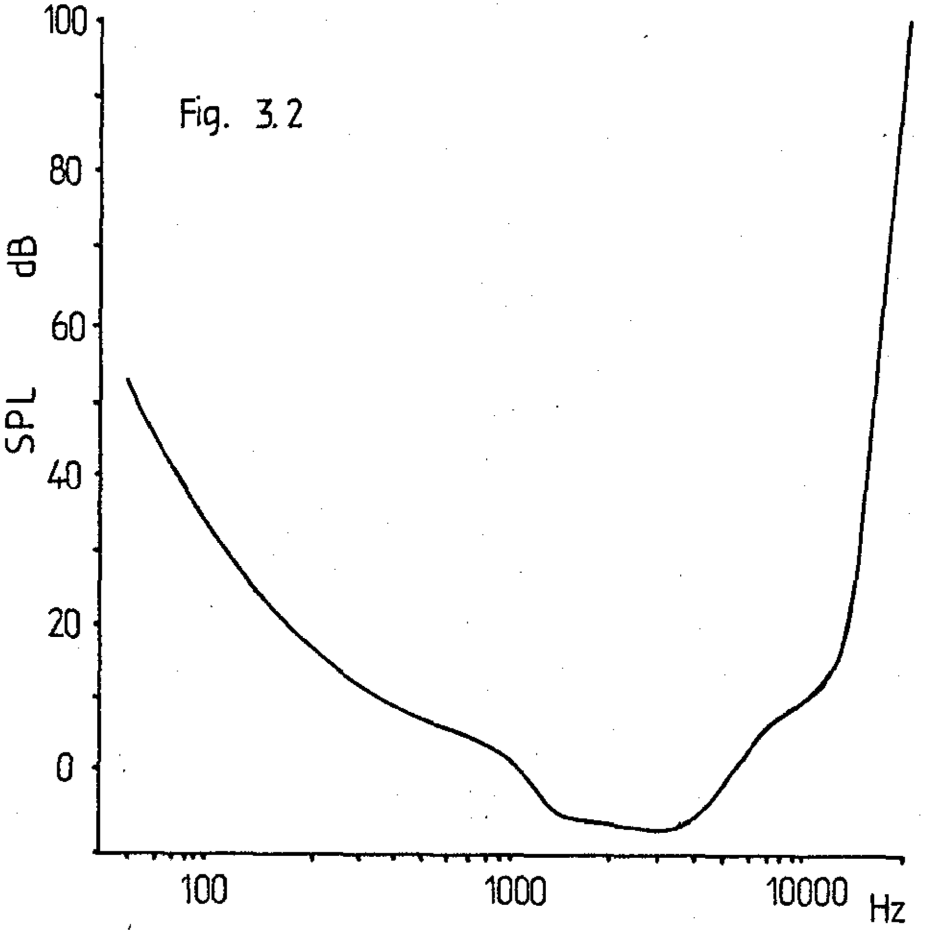


Fig. 3.2

Threshold of Auditory Sensitivity

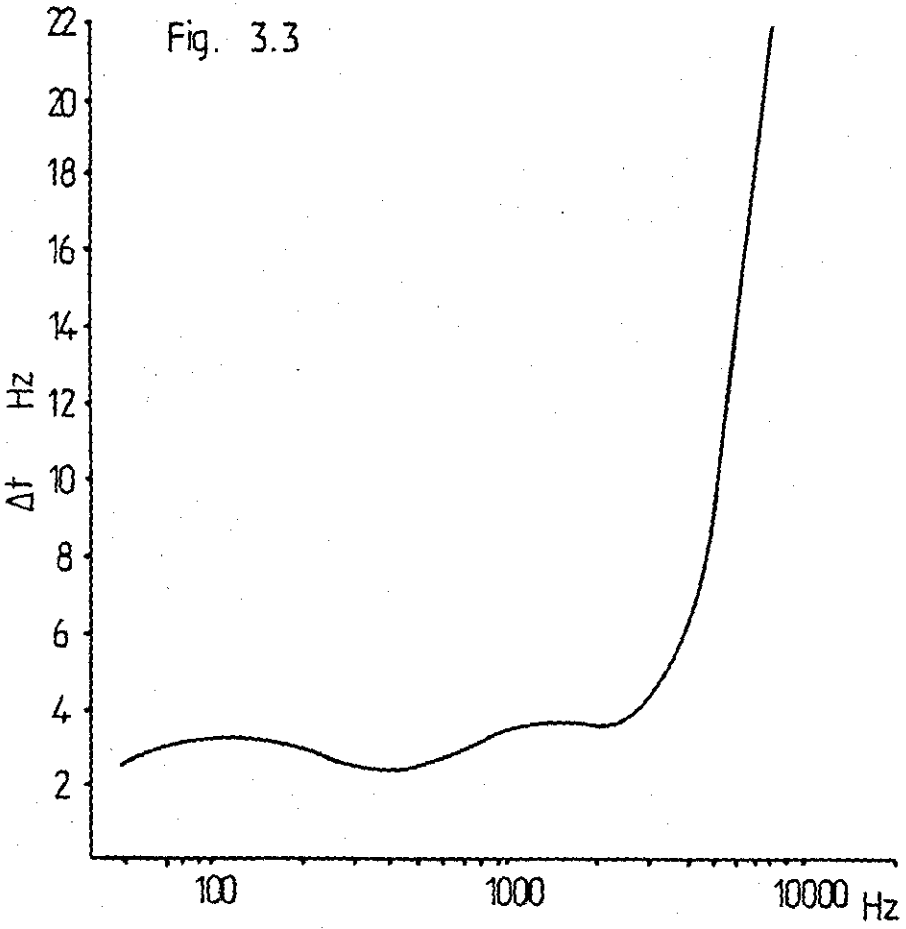


Fig. 3.3

Minimum Perceptible Differences in Frequency

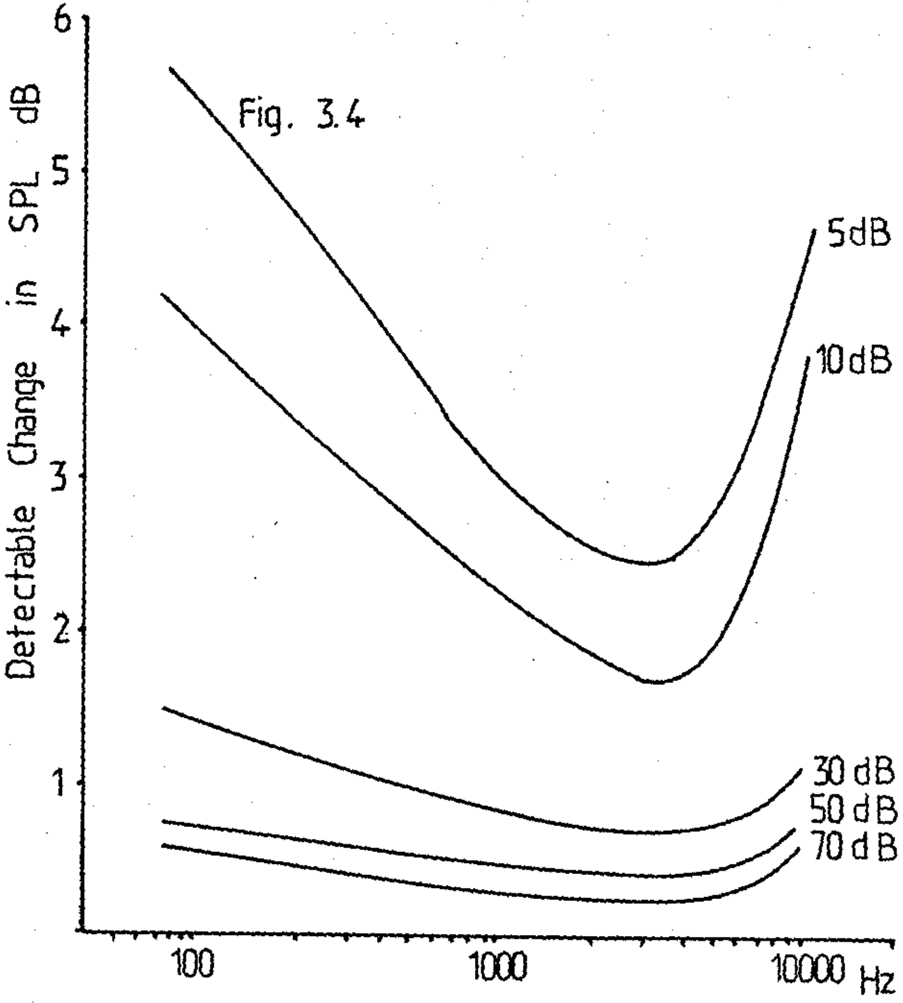
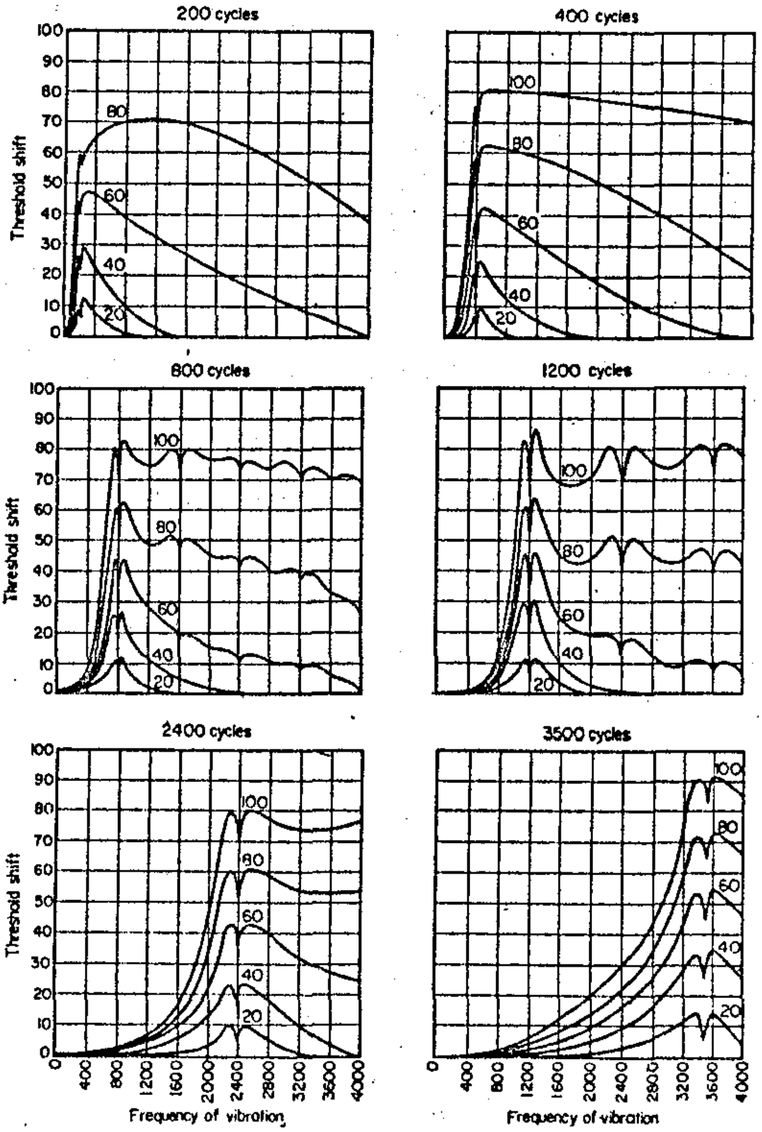


Fig. 3.4

Minimum Perceptible Changes in Amplitude



200 cycles

400 cycles

800 cycles

1200 cycles

2400 cycles

3500 cycles

Fig. 3.5 Masking Curves.

3.2.3 Physical Analysis

3.2.3.1 Analysis Parameters

The snalysis of the musical sounds involved here takes the form of a physical description requiring the simultaneous determination of frequency and amplitude components throughout an observation time which will last for a number of cycle-periods of the signal. The most useful and easily understandable method of presentation is by means of graphs showing the progress of each harmonic of the sound throughout the observation period. This method of presentation enables the physical description to be easily compared with the physiological impression. The equipment available for electronic analysis was a Ubiquious Real-Time analyser and a Hewlett Packard 5451A Fourier Analysis System.

Keeler[1] identifies two reasons for the dearth of study in this area. The first is the complexity of the instrumentation and procedures required, and the second is the problem of correlating the results with those of the steady state, which are in the harmonic-series discontinuous-spectrum format. This problem, the applicability of periodic techniques to mildly aperiodic sounds, is discussed fully in his earlier work[2] in which procedures involving the application of fourier analysis to segments of the transient that were one period long are evaluated.

Earlier studies such as that of Backus and Hundley[3] and Nolle and Boner[4], suggest that the transients play a role, and Mercer[5] recognises the possibility of his analysis being insufficiently complete to indicate the differences which are perceivable to the ear. Backus and Hundley[6] suggest that wall material has little effect on the transient buildup though it seems likely, from discussion with organ builders, that the effects attributable to material are found mainly in this unsteady part of pipe speech. The analysis of pipe onsets is therefore considered vital for this study.

The problems of analysis are then related to the complexity of

[1] Keeler (59) 378

[2] Keeler (60)

[3] Backus and Hundley (3)

[4] Boner and Newman (15)

[5] Mercer (81) 50

[6] Backus and Hundley (3) 994

musical timbre, particularly that associated with the transient parts of musical sounds. For this reason earlier studies[1] did not include precise analysis of transients. In their introduction, Nolle and Boner[2] point out the difficulty of interpreting organ transient oscillogramms, the only method available to most workers, due to the unsuitability of the usual methods of Fourier analysis to signals whose amplitudes are changing. Although rapid calculation of the components is possible now, the application of Fourier transform techniques to the study of musical transients is not straight forward. Principal among the problems is the frequency perturbation associated with organ onsets. The associated change in period length must be accounted for in analysis since the calculation of frequency and amplitude components within a period different from this can produce significant errors.

Of the three parameters used to define a musical sound, phase is usually regarded as the least important, amplitude and frequency information having greater value.[3] Phase information figures rarely in pre-computer analysis of musical sounds and even in recent studies of the importance of phase[4] - both in absolute terms and relative to the other parameters - the authors are unable to make more than speculative judgements about its importance. Phase information, after scrutiny of literature on the subject, was considered unimportant for this study and is not presented in the results. A full discussion of this is found in Appendix A.

3.2.3.2 Physical Analysis Method

The musical transient sounds which are represented by voltage signals, increase in amplitude over a very short period of time equivalent to only a few cycles of the waveform. Various methods of analysing the signals were considered but in the method adopted, analysis is achieved by dividing the signal's onset into a number of equal time duration samples and calculating amplitudes for each sample. It is necessary that the samples, whether they comprise individual cycles

[1] Backus (2)
Trendleberg (122)
Richardson (113)

[2] Boner and Nolle (89) 149

[3] Madsen and Hansen (76) 2

[4] Plomp and Steeneken (96) 409
Zwicker (132) 238

or a small number of cycles, are precisely isolated full cycles of the signal in order that valid computation can be done. Since it is inaccurate to analyse samples involving anything but complete cycles, it is not possible to analyse onsets in regular time periods even if the duration of the period is chosen with regard to the steady frequency of the signal. The H.P. 5451A system does faciliate the segmentation of a waveform which may be retained by the machine. It was not possible, however, to utilise this facility as even if the period length of each cycle could be measured, the sample length can be controlled only within limits set by the window size and block size chosen. The latter is dependent on the storage available and the demands made on this for processing, but for instance in the case of a transient lasting between 50 Ms and 100 mS and using a block size of 1024 bits, the sample length of a 500 Hz signal can be changed only in 23 Hz increments.

The analysis method adopted involves the selection of a sample window size larger than the sample's duration though it does of course, need to take in the whole of the transient to be analysed as in the method discussed previously. Due to considerations about sampling intervals and frequency resolution, the durations chosen are often much larger than the duration of the sample. Here the machine computes accurately the amplitudes and frequency components associated with the actual frequency of the particular sample.

The time domain analysis involves the isolation of the signal by the sampling device, FFT analysis by the HP analyser and subsequent presentation of results in graphical form using the Calcomp computer graphics available on the LUT Prime system. Details of the sampling device and the processing of the results is found in Appendix B, together with detail of the selection of analysis parameters: sampling times, period length, frequency resolutions and bandwidths.

3.2.4 Summary

Analysis is required of quasi-periodic signals in their steady-state and more particularly, of their onset. A suitable method has been investigated for electronic analysis which produces results in a form easily understood and which can be evaluated against the physiological characteristics of man's ear. The latter is important in defining the apparent similarity of sounds. Transient analysis, although not hither to applied to this area, is widely recognised as holding a key to the fuller physical description of all musical sounds.

Physiological criterion involves frequency and amplitude limen, the perception of frequency and amplitude modulation within time period boundaries, the effect of masking and auditory integration times. It is found that, over the range of frequencies and amplitudes involved that masking effects are less at lower frequencies, and small changes in amplitude are noticeable at middle range frequencies where the ear is most sensitive. Physical analysis involves the computation of amplitudes by successive FFT on segments of the signal. Phase information is not presented, though changes in frequency are compared.

3.3 Experimental Techniques

3.3.1 Introduction

Organ pipes have been selected as the subject of this study rather than another instrument because they usually function out of the sight of both organist and audience and can be controlled in the laboratory from a distance. Unlike hand held instruments, in which visual aesthetic qualities are involved, the adoption of a different material if suitable accoustically could be achieved without any need to overcome the aesthetic prejudices of the players. The absence of difficulties encountered by workers examining other instruments, such as the possible influence of keywork, the players hands and even peculiarities of his anatomy on tone, also commend organ pipes for study. Risset and Matthews[1] identified these problems in other wind instruments complaining that:

" Musical instruments are not usually operated by a standardised mechanical player but by human musicians who introduce intricacies, both intentionally and unintentionally. Even if a human player wanted to, he could not repeat a note as rigorously as a machine does. If he has good control of his instrument, he should be able to play two tones sounding

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1 Risset and Matthews (105)

nearly identical, but these tones can be substantially different in physical structure..... The way a player interprets score markings depends both on his technique and sense of style. These closely mingled physical, physiological, psychological and aesthetic considerations complicate the task of the physicist seeking to analyse instrument tones for their characteristic features. "[1]

Changes in embouchure, which can effect tone substantially, must be standardised if there is to be any realistic investigation of musical transients and is certainly necessary for investigations in which resonators of different materials are exited by a common driver. The organ pipe commends itself for this study since its activation depends neither on a player who may influence the tone and will certainly be unable to repeat lip inflections precisely, or on a mechanical device to simulate the player. The pipe can be controlled remotely by electric solenoid pallet valves enabling wind to be admitted to the pipe in a repeatable manner.

Pipes of diapason tone quality are used throughout this study since they represent the dominant colour of organ sound and are found at all pitches. Their scale lies between that of flute stops which have a large resonator diameter compared with the narrower resonator of string toned stops. Due to limitations imposed by the available anachoic room, in which the minimum frequency for recording was 100 Hz, experiments involved pipes with a minimum frequency of 132 Hz.

3.3.2 The Isolation of Resonator from Voicing Effects: Methods Available

The design and construction of most organ pipes, in which the upper lip is integral with the resonator, and the lower lip with the conical foot part, frustrates the investigation of the influence of material on tone quality because of the interrelation of the jet drive mechanism and the resonators' standing wave. Clearly, for work to proceed, each parameter must be investigated independently. One approach is to make test pipes of identical geometry out of different materials. By so doing the effect of materials changes on all aspects of the pipe can be considered simultaneously: the combined effects of the resonator and lip materials. However, since only by microscopic setting can the

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[1] Risset and Matthews (105) 23

languid be set at the same relative position in all pipes with sufficient accuracy and for an accurate measurement, each pipe must be voiced individually and, as has been noted in section 2.4.2, voicing can markedly affect the tone. Experiments so carried out investigate the effect of voicing together with those other parameters and thus the extent of the influence of material on tone is therefore not isolated by this experimental method.

A second approach, in which the resonator's influence is investigated independently of the other parts, and which is known as the common drivertechnique, involves the severing of the resonator from the lower part of the pipe above the foot. The sensitive voicing adjustments, all carried out to the foot, are undisturbed and remain constant for each new resonator tried. This method has been adopted in several studies but may be criticised since the manipulation of the pipe to the extent of cutting the resonator away must in fact produce a new acoustic device, which is not wholly representative of the system which exists in practice.

Information about the extent of changes to pipe tone due to the removal of the resonator presented in other studies[1] show that very little change occurs in the steady spectrum of pipes treated in this way. These findings stimulated interest in the method but since they can not be applied to pipes in general, only to the specific ones evaluated, the preliminary work associated with this study involved careful consideration of the validity of the approach. Whilst the experimental method adopted does in fact assist the isolation of the resonator's function, unequivocal results which can be applied to 'real' pipes may not be produced. This is however, the only method which can provide an insight into the problem of the relationship between material and tone or lead to suggestions for alternative materials and has therefore been adopted in this study. The first method discussed above, involving the comparison of whole pipes made in different materials, is adopted in this present study for experiments concerned with the effects of voicing relative to material. It is also used for the final assessment of a material's suitability, involving voicing by a skilled pipe voicer.

[1] Nolle and Boner (89)

3.3.3 Validation of Common Driver Technique: Steady State Analysis

3.3.3.1 Method

To permit variation of the resonator tube while keeping the foot constant the two parts of the pipe, the resonator tube which has to be mounted upon the lower part consisting of the pipe foot, languid, upper and lower lips - hereafter referred to as the foot - must be held together when the pipe is reassembled. A sleeve or collar was therefore designed to locate the parts. Initial experiments involved analysing the sound to assess the effectiveness of the collar and the extent of the change produced in a substantive pipe due to the modification.

The collar's function is to allow the pipe resonator to be removed and refitted without disturbing the sensitive pipe mouth. It must join the resonator and foot, allow the two tube ends to come together, and prohibit the entry of air from outside the pipe. The collars also facilitate rapid changing of resonators and enable tubes of similar internal diameters but of thicknesses which may be smaller or larger than that of the original resonator to be accommodated.

Since earlier studies have been criticised for basing their conclusions on work carried out on one pipe only, five pipes of different speaking lengths were chosen. These were the C pipes from a 4ft Principal rank. This rank was chosen for experiments because diapason tone is fundamental to the musical quality of the organ and the 4ft Principal is usually the chief manual foundation stop.

The pipes chosen were sounded in an anechoic chamber and analysed by a Ubiquitous Real-Time Analyser. The results were plotted by a pen recorder on graph paper.

Each pipe was sounded using a small windchest made for this purpose and able to accommodate pipes as they would be in an organ as commonly constructed. Wind was supplied from an electric blower located outside the chamber. The pressure was controlled by altering the speed of the motor, adjustment being effected by a Variac transformer. Although the blower was encased and surrounded by expanded polystyrene to reduce its noise, positioning it outside of the anachoic room was imperative in order to preserve the low noise level within the chamber. The tube conveying the wind entered the room through a 3 inch diameter duct through which also passed another plastic tube from the chest to an anemometer and wires from the control device and the microphone too.

The water anemometer monitored the pressure in the windchest. The pipes were mounted on the chest with the pipe foot over a slightly chamferred hole and were supported slightly below the mouth by a rack-board. Below the pipe electro-magnetic pallet magnets (Kimber Allen type D.P.R $1\frac{1}{2}$") controlled the entry of wind into the pipes. These were controlled from outside the chamber.

After the pipes had been checked for cylindricality using internal micrometers they were sounded and analysed. (Experiment 1PR) Subsequently they were marked and the resonators sawn off above the upper lip. Three types of collar were considered and the effect of each noted for each pipe. The collar types were:

Experiment 2PR	Tin plate Collar soft soldered at the seam.
Experiment 3PR	Self adhesive PVC tape.
Experiment 4PR	Soft rubber collar made from 2mm thick rubber joined by Loctite Superglue 3.

3.3.3.2 Analysis

Information about low amplitude constituents of the signal was sought in order that the comparisons of spectra could be as complete as possible, but the initial results from the analyser lacked resolution of low amplitude signals. The sensitivity was therefore increased by attenuating the predominant fundamental frequency by filtering. High pass filters were found unsuitable but a band pass filter set between the fundamental and first harmonic frequency and at maximum at the high frequency end (60 K Hz) worked well, although some graphs do show components at 9.7 K Hz and 19.2 K Hz which are the result of filter interference. Two graphs were therefore plotted for many of the signals examined. From one graph the amplitudes of the first few harmonics were deduced and from the other those of higher frequency. Since in general low magnitude components occur in higher harmonics, the bandwidth chosen varies between the two analyses. The first graphs require less bandwidth than the second ones. This enables the resolution of many important low amplitude components in the latter graphs and, in the first graphs, more accurate measurement of frequency.

3.3.3.3 Results

The graphs in figures 3.6 to 3.9 show the results obtained from the 132 Hz pipe for the rubber collar (experiment 4PR) and uncut version of the pipe (experiment 1PR) Figures 3.7 and 3.9 illustrate how filtering the signals may be used to increase the resolution of the analysis. Comparison of the pairs of graphs, figures 3.6 with 3.8 and 3.7 with 3.9, shows the similarity of harmonic spectra produced by the two versions of the pipe. Results obtained for all five pipes and with each form of collar are more easily compared in the tabulated format presented in table 3.1.

Table 3.1a shows the results from the graphs for experiments 1PR and 4PR and also those for the tin plate and PVC tape collars, experiments 2PR and 3PR respectively. Two non-harmonic partials are noted, at 696 Hz and 984 Hz. Only in the results of one other pipe, 264 Hz shown in table 3.1b is another such partial noted. In this instance it lies between the 7th and 8th harmonics at 1980 Hz. The 696 Hz partial found in table 3.1a is however, the only one which lies in the formant region for the fundamental frequency involved.

Tables 3.1b, 3.1c, 3.1d and 3.1e provide a similar tabulation of the results obtained from graphs for the 264 Hz, 532 Hz, 1080 Hz and 2080 Hz pipes respectively, as has been described for the 132 Hz pipe. The number of detected harmonics varies between the pipes; table 3.1b has 11, 3.1c and 3.1d have 9 each. The pipes at the extremes of the range examined, tables 3.1a and 3.1e have fewest, 8 and 6 respectively.

Table 3.1f is a repeat of the 2PR and 4PR experiments for the 264 Hz pipe. Together with the results presented in table 3.2 which are the results obtained from adjacent pipes to those presented in table 3.1, they were found necessary as is described in section 3.3.3.4.

TABLE 3.1

Validation of Common Driver Technique: Steady-State Analysis Results.

Table 3.1a
132 Hz

Expt.	Collar	filter	HARMONIC											
			1	2	3	4	5		6	7		8		
			FREQUENCY											
								696 Hz			984 Hz			
1PR		nf	68.5	27.5	42									
		+f			42	26	17	10	17		3	4		
2PR	Tin Plate	nf	66	25	40.5									
		+f			43	30	17	12	21		4	6		
3PR	PVC Tape	nf	68	23	40.5									
		+f			40	22.5	13	10	14		3	3		
4PR	Rubber	nf	68	27.5	43									
		+f			43	28	20	11	22		4	5		

Table 3.1b
264 Hz

Expt.	Collar	filter	HARMONIC											
			1	2	3	4	5	6	7		8	9	10	11
			FRQUENCY											
										1980 Hz				
1PR		nf	71	45	32									
		+f			38	35	26	22.5	14.5	6	16	0	11	10
2PR	Tin Plate	nf	70	54	36									
		+f			35	37.5	24.9	18	18.5	6	11	11.5	9	2
3PR	PVC Tape	nf	72	50	39									
		+f			39	37.5	24	23	22	5	12.5	16	10	3
4PR	Rubber	nf	72.5	45.5	32.5									
		+f			32.5	34	24	14	16	9	0	8		

Table 3.1c

532 Hz

Expt.	Collar	filter	HARMONIC								
			1	2	3	4	5	6	7	8	9
			FREQUENCY								
1PR		nf	62	53.5	31	33					
		+f			31	32.5	27	13	15	15	2
2PR	Tin Plate	nf	62	57	34.5	35					
		+f			35.5	35	15	8	12		
3PR	PVC Tape	nf	62.5	51	37	33.5					
		+f			41	35	28	10	16	12	
4PR	Rubber	nf	63	55	41	33					
		+f			41	32.5	27.5	16.5	11.5	14.5	4.5

Table 3.1d

1080 Hz

Expt.	Collar	filter	HARMONIC								
			1	2	3	4	5	6	7	8	9
			FREQUENCY								
1PR		nf	70.5	52.5	37	37.5	31	26.5	22.5		
		+f			37	37	31.5	27	24	21.5	18
2PR	Tin Plate	nf	66	55	31.5	32	28	28			
		+f			37.5	32.5	30	30	15	21	7
3PR	PVC Tape	nf	68	55	36.5	33	32.5	33	16.5		
		+f			38	30.5	31.5	33	20	20	15
4PR	Rubber	nf	71.5	56	38	38	34				
		+f			39	39	35	33.5	27	18	18

Table 3.1e

2080 Hz

Expt.	Collar	filter	HARMONIC											
			1	2	3	4	5	6						
			FREQUENCY											
1PR		nf	51	25	22.5	10	8	6.5						
		+f												
2PR	Tin Plate	nf	50.5	27.5	17.5									
		+f												
3PR	PVC Tape	nf	49	14	14	3	4.5							
		+f												
4PR	Rubber	nf	52.5	24.5	26		15							
		+f												

Repeat of 264 Hz Analysis

Table 3.1f

Expt.	Collar	filter	HARMONIC											
			1	2	3	4	5	6	7	8				
			FREQUENCY											
2PR4^R	Tin Plate	nf	71.5	47	30									
		+f			32	36	27	15	18.5	13				
4PR4	Rubber	nf	72	45	31									
		+f			32	35	26	15	17	11				

TABLE 3.2

Repetition of 264 Hz, 1080 Hz and 2080 Hz analysis with adjacent pipes: 280 Hz, 1200 Hz and 2400 Hz

Table 3.2a
R 280 Hz

			HARMONIC						
			1	2	3	4	5	6	7
Expt.	Collar	filter	FREQUENCY						
7PR	Rubber	nf	75	50	43	42.5			
		+f				42	33	24	21
8PR	Rubber	nf	70	49	41	39			
		+f				39	33	27	22

Table 3.2b
R 1200 Hz

			HARMONIC						
			1	2	3	4	5	6	7
Expt.	Collar	filter	FREQUENCY						
7PR	Rubber	nf	57	39	31				
		+f			30	21	27	20	17
8PR	Rubber	nf	60	38	29				
		+f			30	22	20	11.5	16.5

Table 3.2c
R 2400 Hz

			HARMONIC			
			1	2	3	4
Expt.	Collar	filter	FREQUENCY			
7PR	Rubber	nf	63	36	26	6.5
		+f				
8PR	Rubber	nf	58	39	23	5
		+f				

NOTE

All dB Scales
re. 2×10^{-5} N/m^2

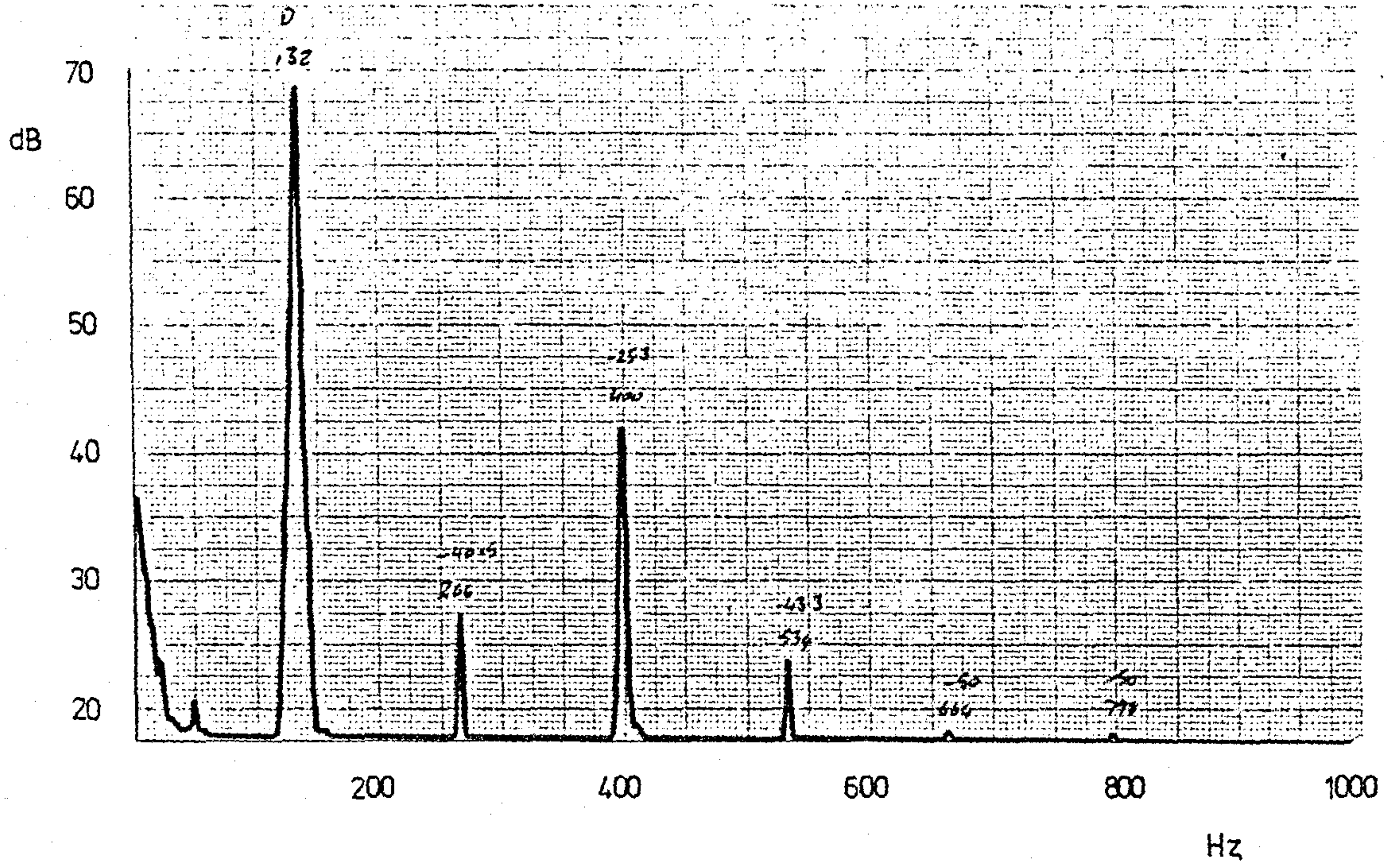

Fig. 3.6 1PR 'C' 132 Hz

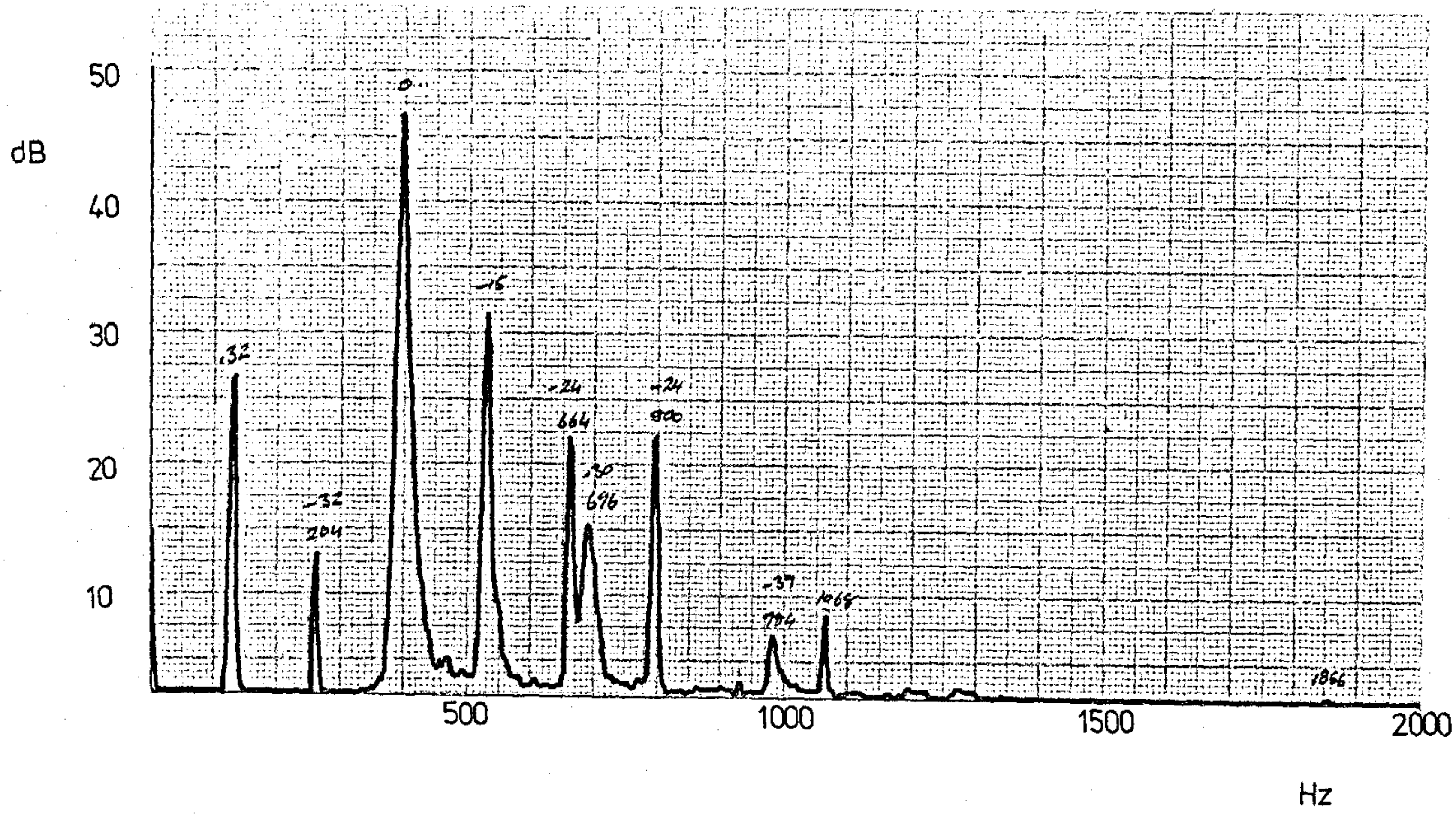

Fig. 3.7 1 PR 'C' 132 Hz with 370 Hz Filter.

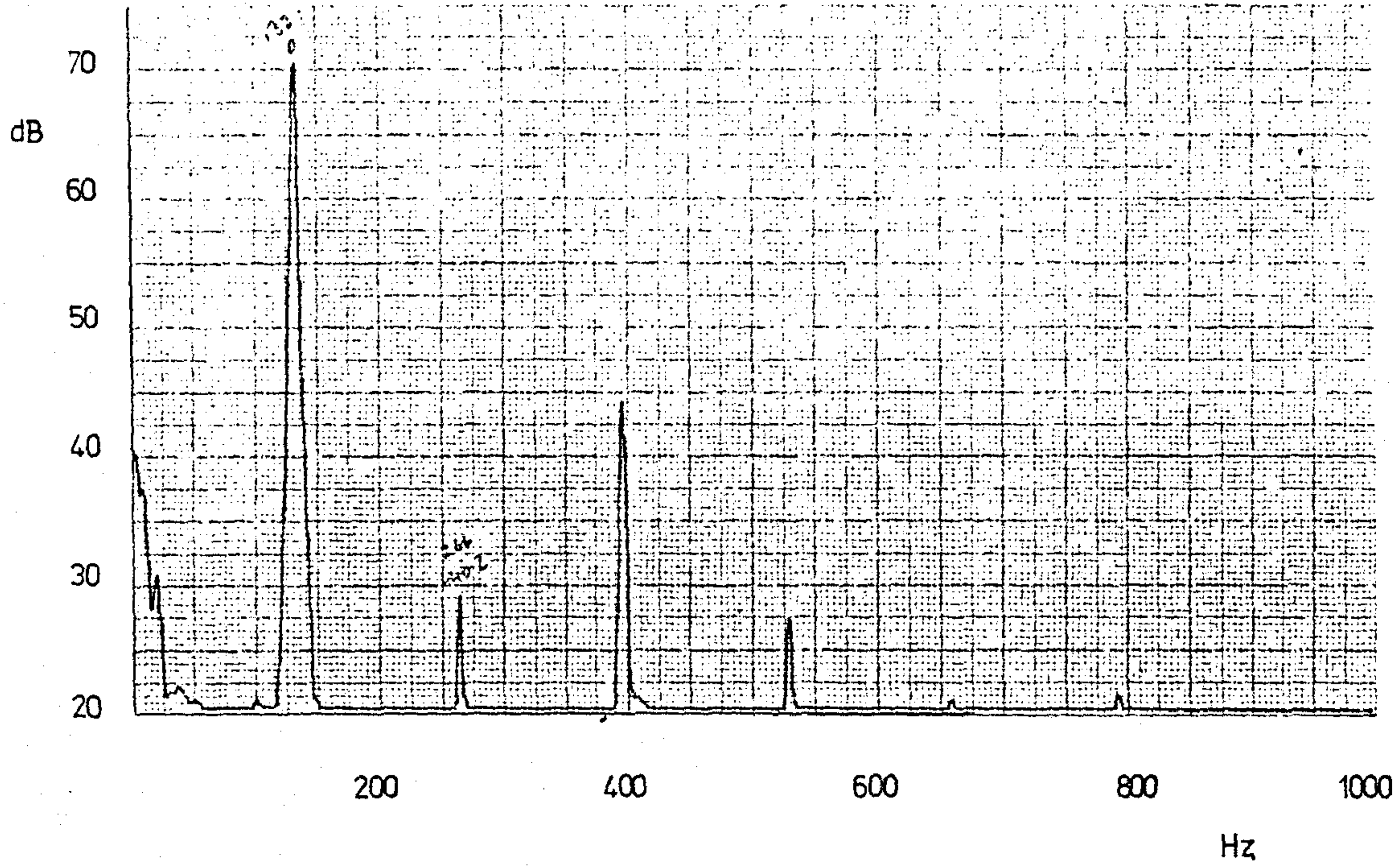

Fig.3.8 4 PR 'C' 132 Hz

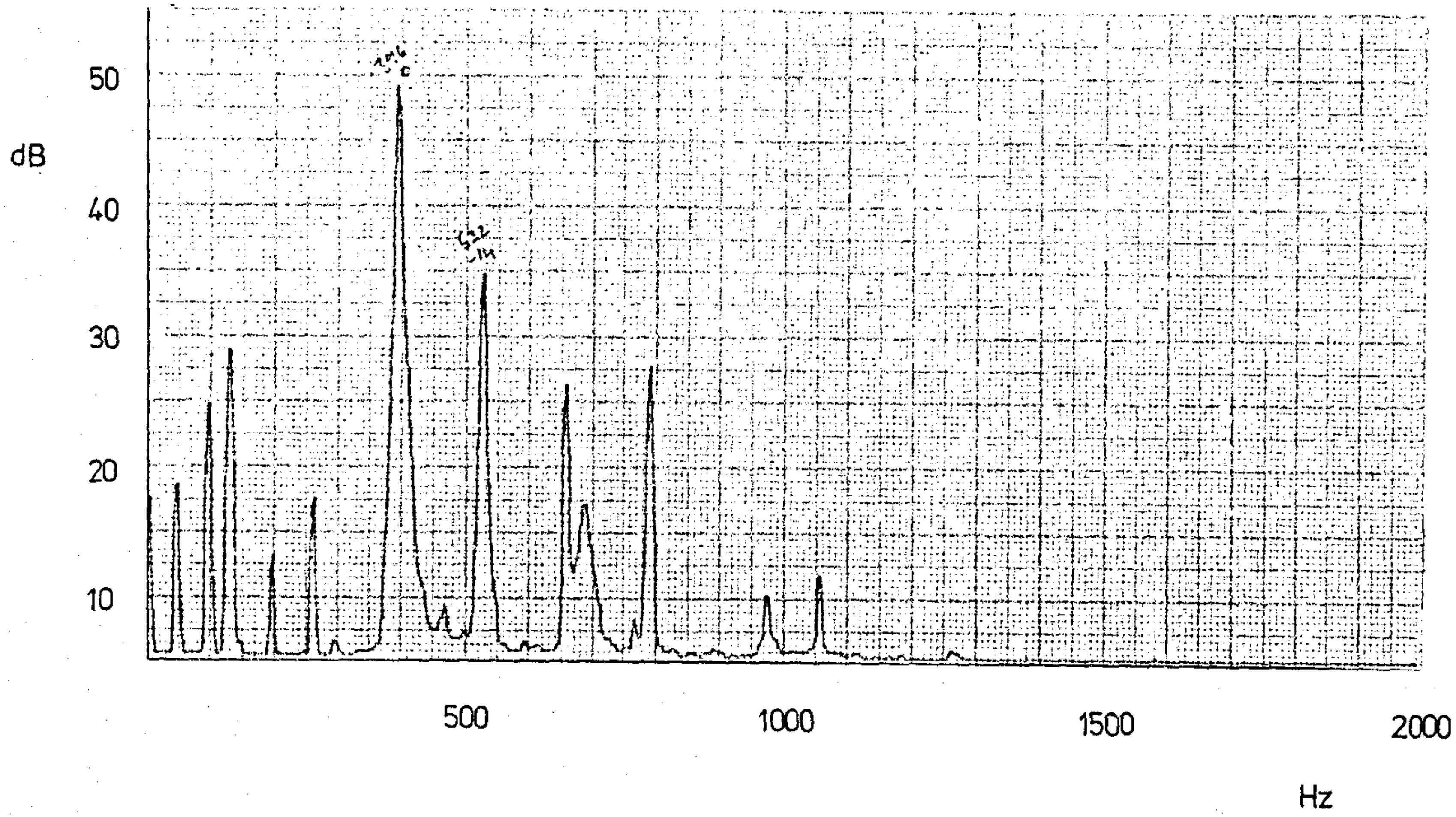

Fig. 3.9 4 PR 'C' 132 Hz with 370 Hz Filter.

3.3.3.4 Discussion

Although the sheet metal collar was comparitively easily made and fitted, the results for the 132 Hz pipe show slight changes in the spectrum in comparison with the original. The fundamental and second harmonic are slightly reduced in amplitude. However, since the rubber collar was found to yield a spectrum very similar to that produced before the pipe was cut, this change can not be attributed to the modification which had been made to the pipe. The most likely reason for the result is that the collar allowed some air to enter the pipe where the two sections meet. The tape used (experiment 3PR) was insufficiently wide to enable the heavy resonator to be mounted firmly on the foot. The discrepancies shown by the analysis probably originate therefore in the incorrect seating of the parts. The sound spectrum using the rubber collar shown in fig. 3.8 and 3.9 however, was very similar to the uncut pipe's shown in fig. 3.6 and 3.7; slight discrepancies occurring are expected as has been shown. It appears therefore, that in this instance the mutilation has not changed the sound produced.

The 532 Hz pipe exhibits similar results to the 132 Hz pipe. Compared with the uncut original, the pipe using the metal collar shows various slight changes and significant attenuation of the 5th and 6th harmonics. The absence too of the higher harmonics which are reduced when air is allowed into the pipe through the resonator[1] suggest that this collar also did not seal well. The similarity of both 3PR and 4PR to the original is striking though both exhibit a 10 dB increase in the level of the 3rd harmonic. The presence of this discrepancy indicates some physical change in the pipe. Since all other harmonics were so similar and the results for C 132 Hz has shown so little change in the pipes after being cut and then reassembled using the rubber collar, consideration was given to the possible effects of slight damage to the pipe mouth. Pipes in later experiments were protected against damage, but these first ones, whilst being carefully handled, could have sustained a slight bump between the times of the two runs. This question is developed further and repeat experiments show that this is in fact the case, and that once again the rubber collar proves suitable for the purpose.

It is certain that the smallest pipe, 2400 Hz, was damaged when

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[1] Organ builders are familiar with this phenomenon and use it deliberately in certain stops, particularly Harmonic Flutes

the resonator was cut. The other pipes had been successfully and easily cut with a junior hacksaw, the set of whose teeth had been reduced with an oilstone to minimise the material removed. Each pipe had been supported in V blocks whilst this was done. The pipe however, was so thin and difficult to hold that it was dented before the saw began to cut. The changes evident from the results even when assembled with a rubber collar were not therefore unexpected. The metal collar did not commend itself for this tiny pipe as in fitting it damage was also done. The soft metal tended to buckle as it was pushed onto the collar.

The analysis of C 264 Hz shows again the value of the rubber mounting collar for reassembling the cut pipe. All the components are similar between 1PR and 4PR apart from the 6th harmonic which is 12 dB less than the level in the original uncut analysis. This is a feature which cannot be ignored and to examine this further, experiments 2PR and 4PR were repeated. The results are shown in Table 3.1f. Comparing PR2 with $PR2^r$ it is notable that two important harmonics now show some significant reductions in their magnitudes. These are, 2nd harmonic (7dB) and 3rd harmonic (4 dB). PR4, $PR4^r$ and $PR2^r$ are similar. It would appear then that some change may have occurred during the course of experiments 2, 3 and 4PR (which were all carried out on the same occasion, 1PR had been done previously).

Finally, C 1080 Hz results commend none of the collars. A 4.5 dB change in the fundamental's amplitude, and 5dB attenuation of the 4th harmonic using the metal collar and a similar attenuation using the tape, together with the similar increase in the magnitude of the 2nd harmonic, would suggest that cutting the pipe had affected it adversely if these characteristics were also found in the results from the rubber collar. On the contrary, here the fundamental is back to strength as is the 4th harmonic, but the 2nd is still greatly increased.

It is not possible to conclude from this result anything about the efficiency of the collars. The experiment was therefore repeated using a C-sharp pipe and rubber collar. Also repeated because of speculation about damage effecting the results were C 264 Hz and 2400 Hz. The appropriate adjacent pipes were utilised for these too.

Great care was taken in handling the pipes. The experience gained of cutting the first pipes was advantageous and enabled this to be done more confidently. Each pipe foot was provided with a foam protector which amply covered the mouth.

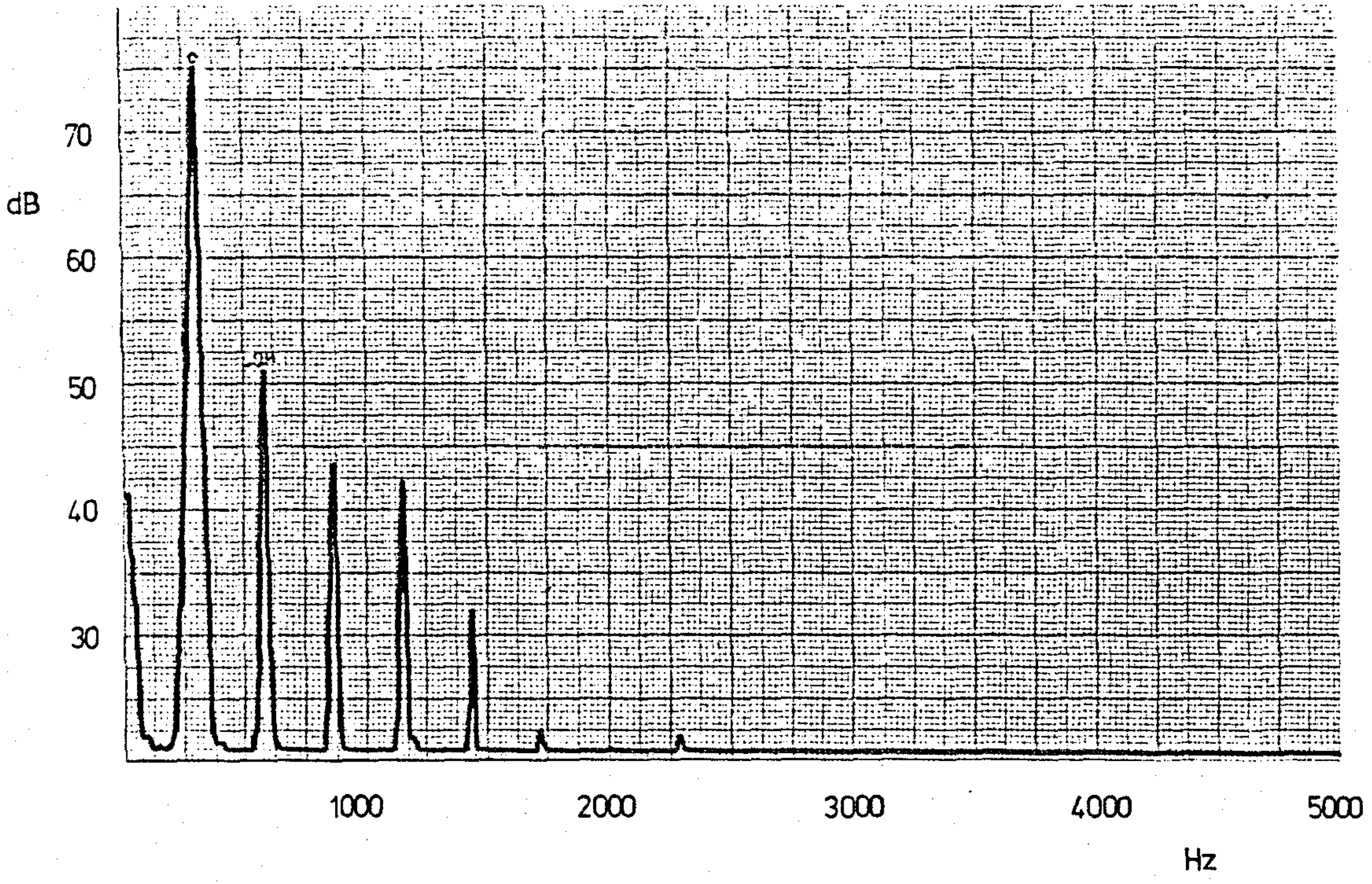

Fig. 3.10 7 PR 'C#' 280 Hz

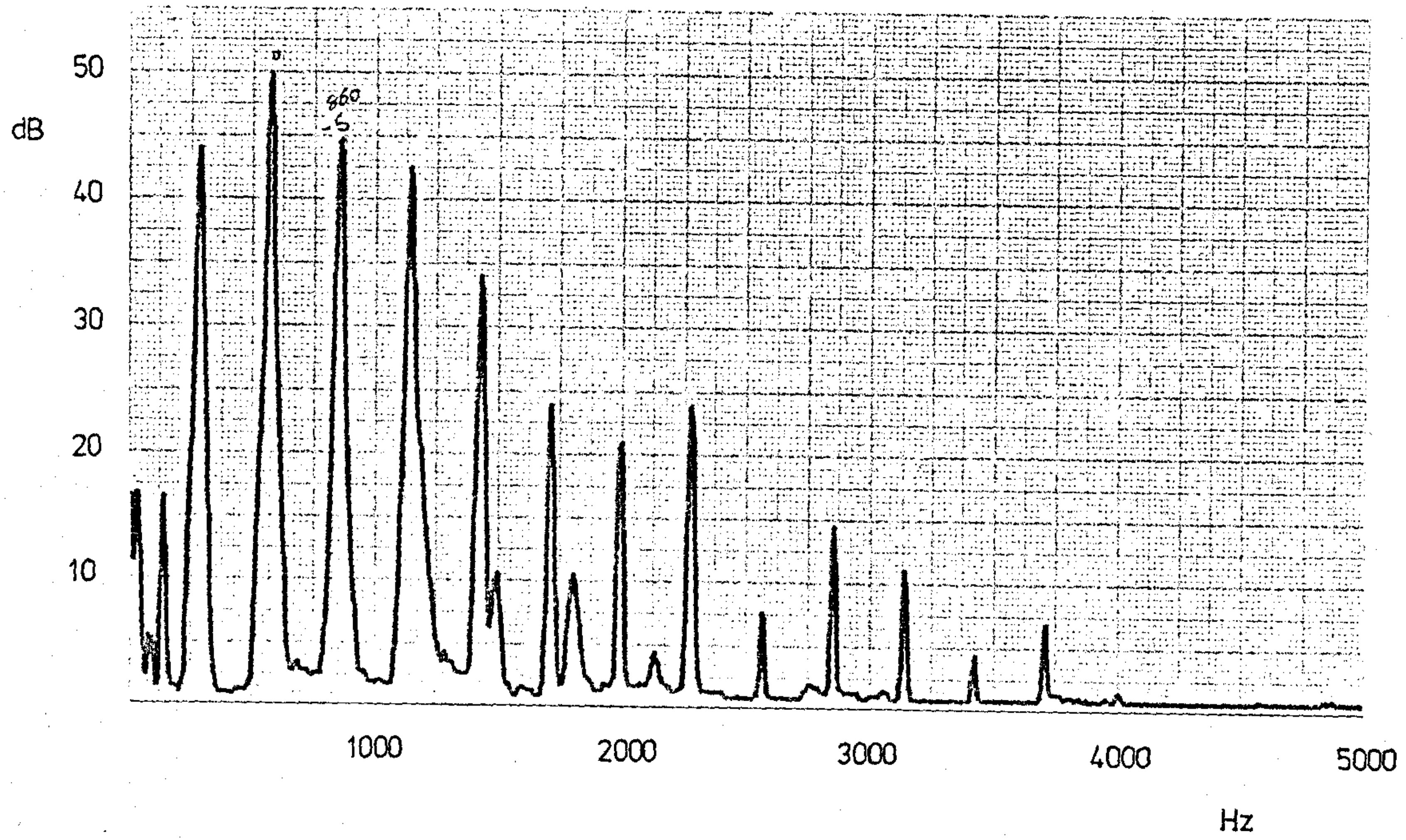

Fig.3.11 7 PR 'C#' 280 Hz with 550 Hz Filter.

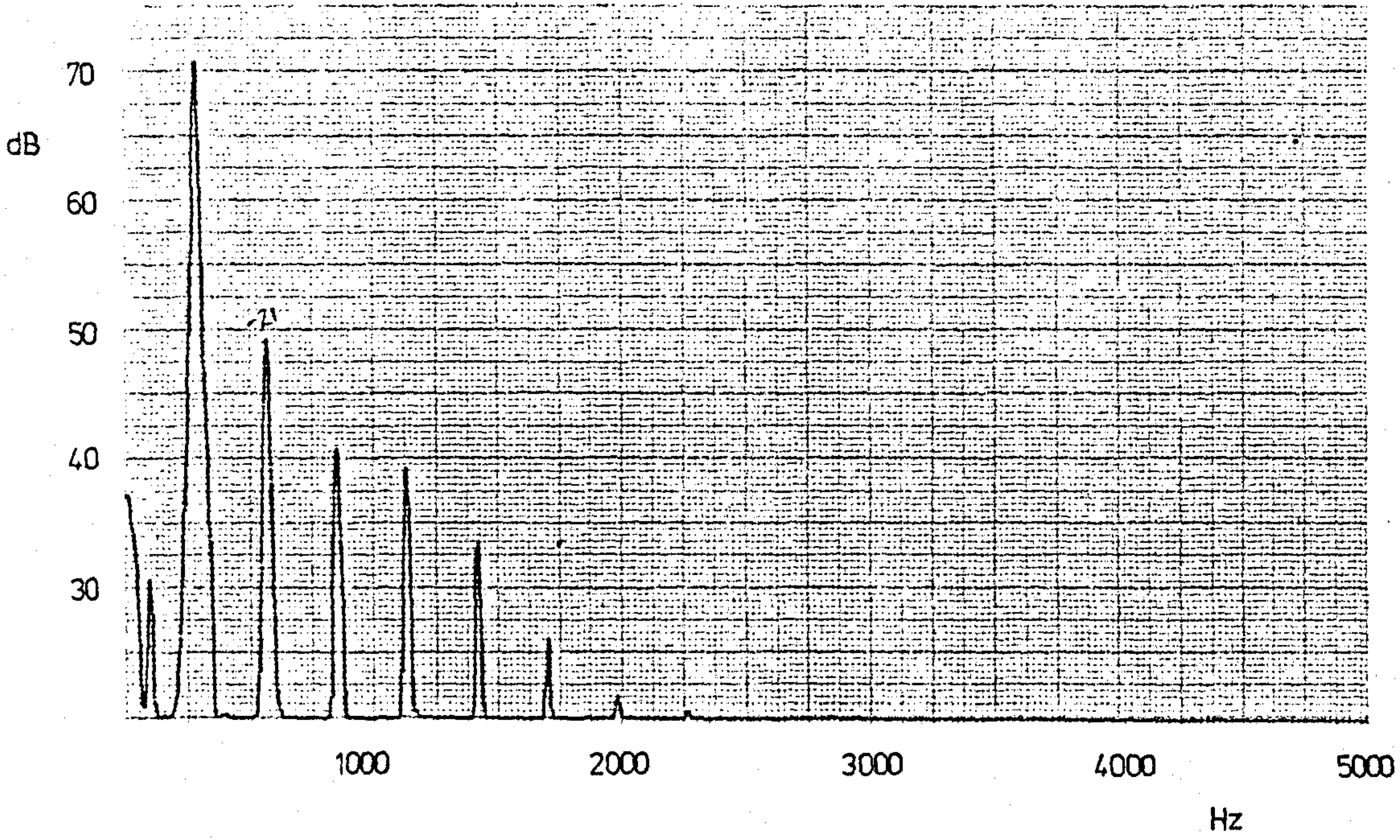

Fig. 3.12 8 PR 'C♯' 280 Hz

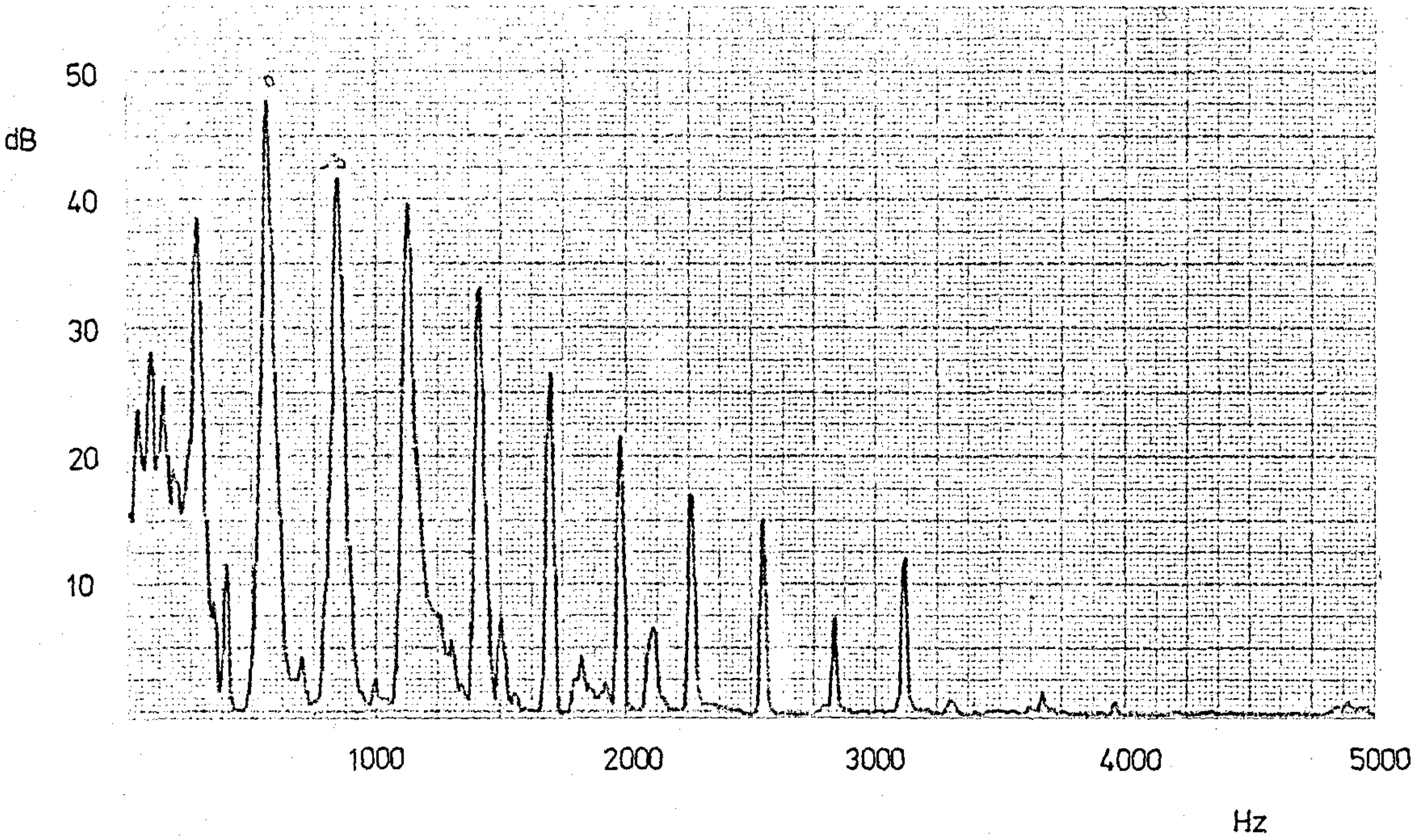

Fig. 3.13 8 PR 'C#' 280 Hz with 550 Hz Filter.

The results with C sharp 1200 Hz pipe and the cut pipe using a rubber collar and 280 Hz Table 3.2 show much better correlation between the uncut and rubber collar. Fig 3.10 to fig. 3.13. The 3 dB reduction in the fundamental amplitude found in both results, the most serious deviation, is within the limits of the error expected. Since this does not occur in other results it is not considered as a failing of the collars.

The results for the smallest pipe is also found to be similar showing close correlation, but a reduction in the amplitude of the fundamental. The presence of this change in all three pipes seems to suggest either a slight change in positions of the microphone between runs or perhaps a difference in wind pressure.

3.3.3.5 Conclusions

From the above results it is apparent that the effect on the steady tonal spectra is minimal for cutting the pipes and joining them. Although the results did show some changes it appears that this was caused by damage. This can be avoided in further work. For the effect to be deemed important it must be seen in most results. This was not the case. The method of using rubber mounting collars fulfils the criterion set out for the collars, enabling the resonator to be changed quickly providing a good seal both for tubes having a similar wall thickness and also for those having slightly larger or smaller thickness.

3.3.4 Validation of Common Driver Technique: Onset Analysis

3.3.4.1 Introduction

The technique of removing the resonator from a pipe foot and replacing it with another has been used in steady state analysis by others, although the rubber mounting collar, with its advantages over other methods, has not been adopted elsewhere. The effects on the onset of pipes of cutting and joining the two parts of the pipe has not been previously investigated. It is vital that changes in the onset tone are minimal and physiologically unperceivable if this method is to be useful in the study of materials and tone quality. The following experiment investigates the common driver technique in terms of its effect on pipe onset tone.

3.3.4.2 Method

Using appropriately sized rubber mounting collars, as in the previous experiment, two pipe resonators were cut above their mouths, remounted and their onset analysis compared with a similar analysis performed before the pipes were cut. The experimental arrangement was the same as in the previous experiment with the microphone 2 metres away from the pipe and 1 metre from the anechoic chamber floor. The pipes stood on 60 mm Wg of wind.

Two similar open metal pipes were chosen. One was voiced with a 'chiff' onset which is characteristic of Classical diapasons, and the other had an organ flute tone. Comparisons can therefore be made between the effects of the experimental technique on these two classes of pipes which figure prominantly in our discussions of the effect on tone of pipe fabrication materials.

3.3.4.3 Results

The results of this experiment, the onset analysis of the two pipes before cutting and when reassembled are shown in figures 3.14 and 3.15. In each instance the y-axis provides a dB scale and the x-axis shows the time elapsing in mS after the pallet valve had been activated. Five harmonics are shown in each of the graps. For ease of comparison figures 3.14a and 3.15a, the flute pipes onset are grouped together as are figures 3.14b and 3.15b, the onset of the diapason pipe. Each pipe's onset lasts for about 140 mS, and begins about 29 mS after the pallet valve is activated. All the graphs display a rapid initial onset which becomes smoother towards the end of the period. The second harmonic in the diapason's onset is quite different from that of the flute pipe rising very quickly, falling off in amplitude and rising again more slowly in the first 80 mS.

3.3.4.4 Discussion

The graphs relating to the flute pipe, numbers 3.14a and 3.15a, show a more rapid onset of the fundamental and 2nd harmonic in the reassembled pipe. It reaches the point where the initial onset ends and gradual buildup begins about 10 mS before the original pipe. The 3rd,

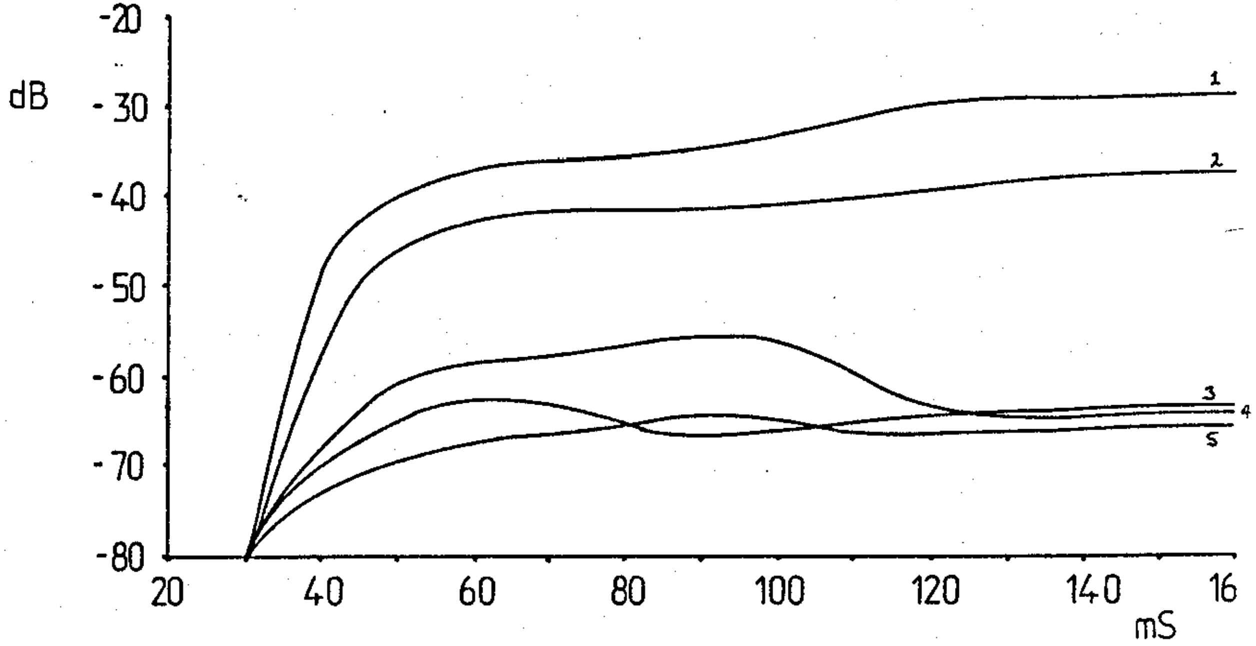

Fig. 3.14a Flute Onset - Uncut

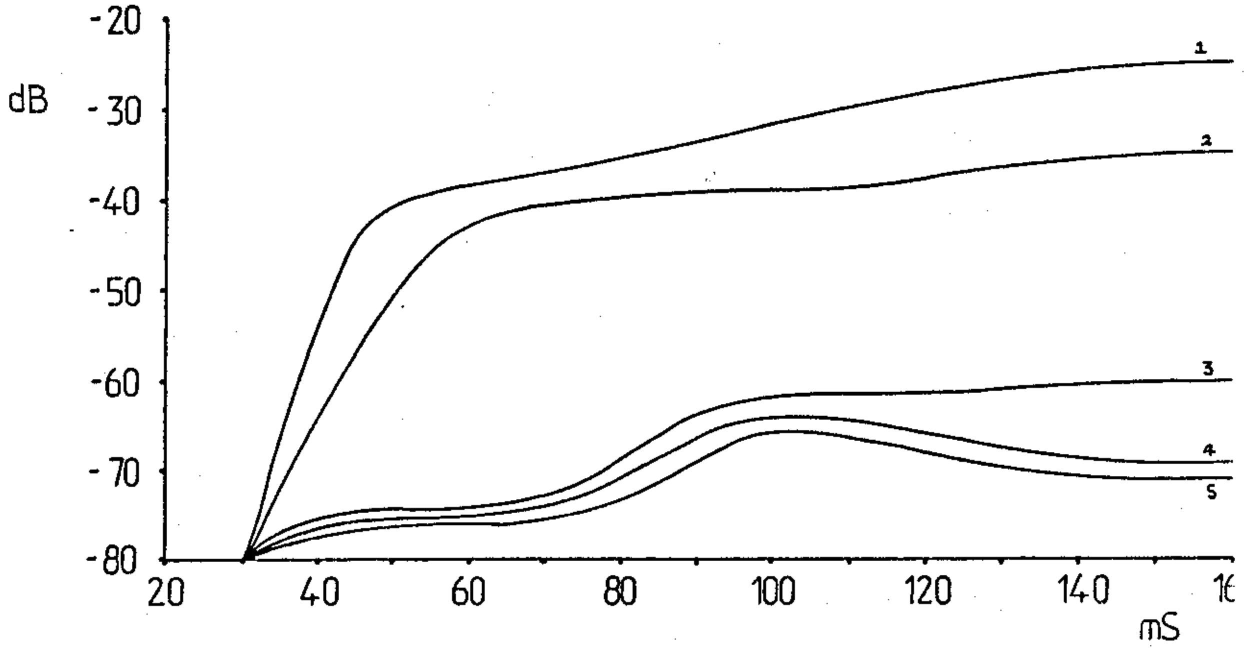

Fig. 3.15a Flute Onset - Reassembled

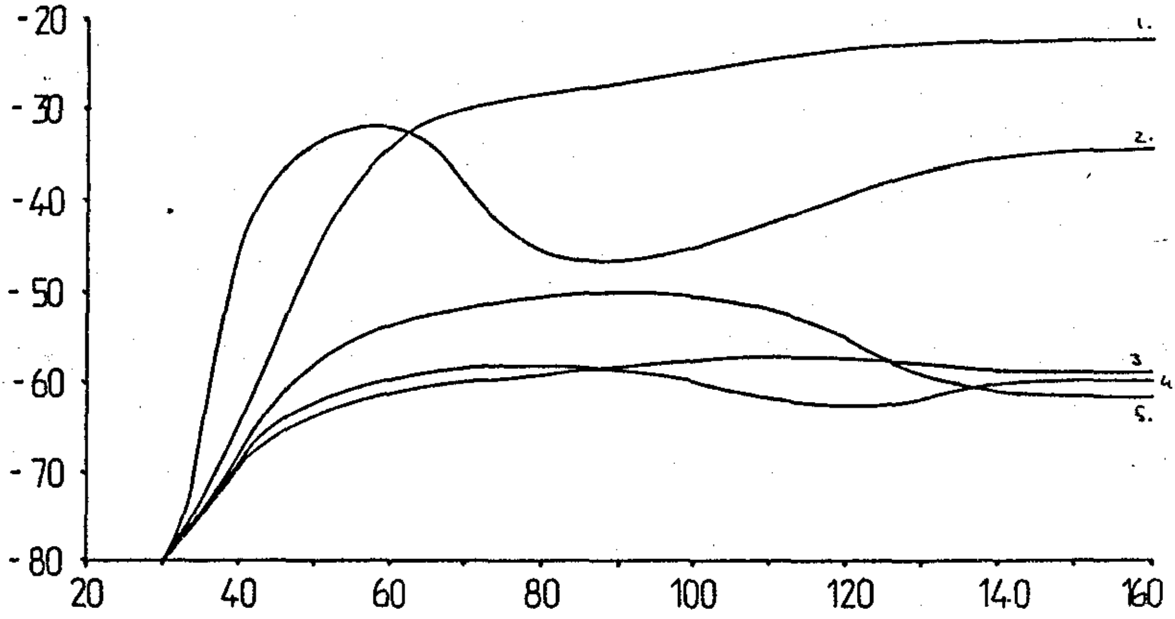

Fig. 3.14 b Diapason Onset - Uncut

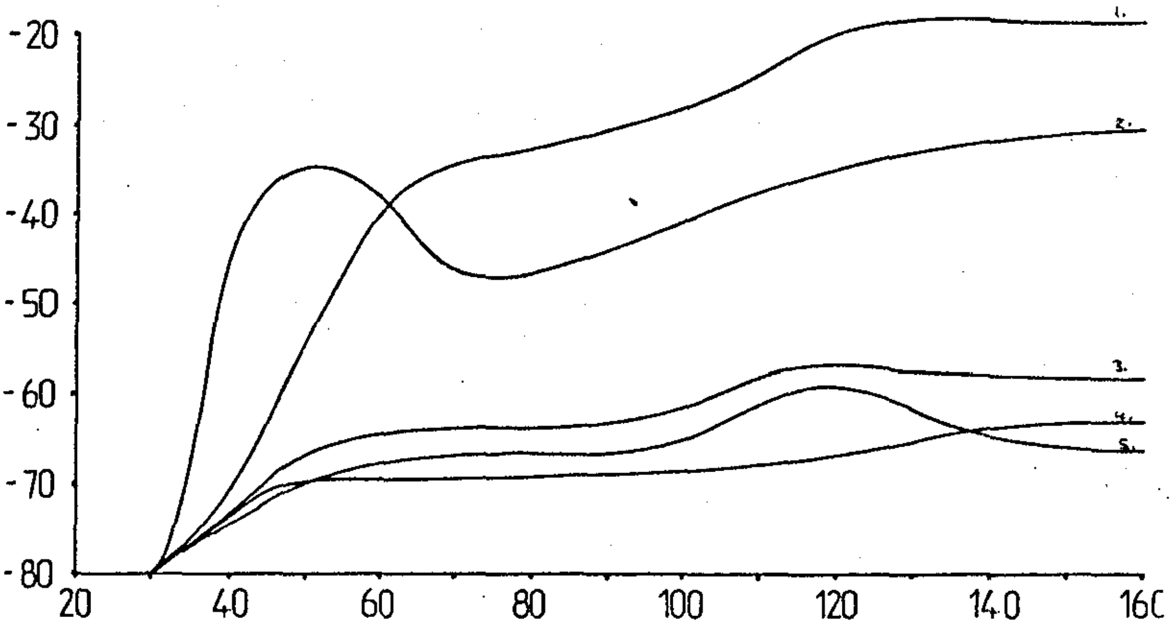

Fig. 3.15b Diapason Onset - Reassembled

4th and 5th harmonics are smaller in the cut pipe during the initial part of the transient, though the 4th and 5th finish at similar levels in both instances. The 3rd harmonic remains constant at the level it has attained by 100 mS in this pipe, but in the uncut one it falls after this duration and ends 6 dB below the level of the other. This observation is also true of the onset of the diapason toned pipe shown in figures 3.14b and 3.15b. Again the 3rd harmonic ultimately reaches a level in the reassembled version which is several dB larger in amplitude than in the original. It is curious that both the final levels shown in figures 3.14b and 3.15b should be similar and those in graphs 3.14a and 3.15a, but they differ in the level of the 3rd harmonic.

Graphs 3.14a and 3.15a show clearly the origin of the 'chiff' onset. It is produced by the more rapid rise of the 2nd harmonic than the fundamental. In both graphs the character of the signals is the same: the rapid onset of the 2nd harmonic to a level close to its final amplitude, is followed by an equally rapid decay and a slower second buildup lasting more than twice the duration of the first. The fundamental builds up gradually, slower than in the diapasons' onset, and reaches the level of the 2nd harmonic only after the latter has begun to decline from its first peak. In the cut pipe the slight overshoot in the fundamental's amplitude near the end of the transient, is more noticeable than in the uncut version. The gradual buildup, after the initial stage, in the 3rd, 4th and 5th harmonics in graph 3.15a, compares with a larger amplitude 3rd in graph 3.14a which decays towards the end of the onset.

Despite the differences noted, the graphs show that the characteristics of the onsets noted in the analysis performed before the pipes were cut, remain inspite of the manipulation associated with the experimental method. These predominant effects are those which are noted by our hearing and effect our impression of rapidly changing sounds. The change in levels of low amplitude components, particularly the 3rd whose level is 25 dB below the fundamental's, do not signify a perceivable change in the onset tone which could negate the use of the method. In fact, the similarity of the results is striking and confirms the suitability of the technique for the study of organ pipes.

3.5 Summary

Time domain analysis of labial organ pipe onsets play an important role in the work presented here. Methods of overcoming the serious practical difficulties arising because of the inherent period-length changes associated with all musical sounds have been discussed, and the design and operation of the sampling equipment has been described. The application of such analysis to the study of wall material effects on tone, and also the pertinent interpretation of these physical results by comparison with physiological considerations, are disparate features of this work.

The analysis technique thus evolved is used to validate the experimental technique which necessitated the dissevering of the resonator from the pipe foot and mouth parts and their subsequent reassembly. The isolation of the effects of lip material is the single most important experimental consideration without which the investigation of resonator material independently of voicing changes would not be possible. The results of the analysis show the suitability of the technique of reassembling the parts using a rubber mounting collar and also demonstrate the ability of the analysis equipment to identify the features of two characteristic organ pipe onsets.

Also discussed is which of the parameters used to define a musical sound will be presented in the results. Amplitude data is of course, most important and frequency perturbations are followed within the limitations of the analysis equipment. Phase information appears to contribute little to the subjective impression of sounds and is, therefore, not presented.

Chapter 4

EFFECT OF RESONATOR WALL THICKNESS AND MATERIAL

4.1 Introduction

Experimental work, it has been shown, is required to clarify suppositions and expand existing knowledge of the changes in tone quality produced in labial organ pipes due to the physical characteristics of the material in which the body is fabricated. Four areas for experiment are identified in section 2.4 . These are:-

1. The multifarious conclusions about the effect of pipe resonator material on steady state tone presented by previous researchers.
2. the relative effects of voicing and material on tone.
3. the link between tone quality, wall thickness and elasticity of the material.
4. the appropriation and validation of the sound radiation theory to the question of pipe material and tone.

Five specific aims for the experimental programme are identified from these areas where further investigation has been shown to be necessary. These are:-

1. to assess the effect pipe resonator material has on steady-state tone quality.
2. to assess the effect of pipe resonator wall thickness on onset transients.
3. to assess the effect of resonator wall material on onset transients.
4. to show whether voicing adjustments can elicit the characteristic onsets associated with pipes made in certain tin-lead alloys from pipes made in other alloys of the same materials.
5. to use Backus and Hundley's theory to suggest suitable wall thickness for pipes made in other materials.

Six experiments are described in the following pages and in the next chapter the results are used, together with the material discussed in the review of literature, Chapter 2, to formulate an hypothesis about the relative influence of four tone-influencing parameters: wall thickness, wall material, lip material and voicing, Chapter 5.

The first experiment, described in section 4.1, compares the steady spectra produced by pipe resonators of different materials and section 4.3 gives an examination of Backus and Hundley's theory which links pipe geometry with wall material elastic modulus. The experiment at section 4.4 describes the investigation of the influence of wall material and wall thickness on tone quality. The question of voicing's effect on tone is considered in three experiments, described in section 4.2 . The extent of the tonal change possible by voicing adjustments to the pipe lips is considered in the first voicing experiment and in the third, because of the suggestion by H. L. Fletcher[1] that pipe attack may be influenced significantly by pressure, the effect of pressure is investigated. The second voicing experiment involves a pipe voicer who attempted to elicit similar tone quality from pipes made in different pipe metal alloys.

4.2 Comparison of Steel and Pipe Metal Resonators Steady-State Spectra

4.2.1 Aim

Since any effect on the tone produced by a pipe's resonator due to the material from which it is made appears, from the work of Backus and Hundley[2] to have little to do with wall vibrations, it is likely that the effect is linked to the yielding qualities of the walls. This experiment was designed to enable a comparison to be made of the steady-state spectra produced by two materials having different moduli of elasticity. The data will be compared with the results of other researchers.

4.2.2 Method

Two resonators were prepared for each pipe foot. One, the pipe metal resonator belonging to the foot having a modulus of elasticity of 3.019×10^{11} dynes/cm^2, the other a steel tube whose modulus was 29.5×10^{11} dynes/cm^2. These were in turn located on the pipe foot and the pipe sounded and analysed as in section 3.2.2.2 . This experiment was repeated on a second occasion, the microphone position having been altered in order to demonstrate that a different sound quality will be detected by listeners at different distances from the pipe. For the first run the microphone was 3 metres from the windchest and 1.5 metres above the floor,

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[1] Fletcher (40)

[2] Backus and Hundley (9)

this being reduced on the second occasion to only 2 metres away and 1 metre from the floor.

The pipes selected were representative of each octave of the rank. They were chosen on the basis of the closeness which their internal diameters could be matched with the sizes of commercially available cold drawn seamless steel tubes from which the resonators were made. The following tube sizes were chosen:-

	Steel Tube Int. Diam.	Wall Th'nss.	Pipe metal Wall th'nss.
140 Hz	72.9 mm	1.6 mm	1.11 mm
280 Hz	42.1 mm	1.2 mm	0.72 mm
560 Hz	23.6 mm	0.9 mm	0.576 mm
1200 Hz	13.6 mm	1.2 mm	0.48 mm
2400 Hz	8.6 mm	1.2 mm	0.4 mm

It proved impossible to produce steel tubes similar in thickness to the pipe metal ones, but, from the results of similar experiments - see section 2.4.1 - this should be of little consequence. The wall thickness shown are the closest available. The pipe metal resonators were cut from the foot parts of their respective pipes and measured. The steel tubes were then machined to length.

4.2.3 Results

The results of the first run of this experiment are found in table 4.1 and those of the repeat experiment in table 4.2 . As in the results described in section 3.2.2.3 , but with the exception of the 2400 Hz analysis (figure 4.3), two graphs are produced for each signal by the real-time analyser. The second graph, figures 4.1b, 4.1d, 4.2b and 4.2d, using a filter, provides greater resolution of higher harmonics, whilst lower components are indicated on the unfiltered graphs, 4.1a, 4.1c, 4.2a and 4.2c. High pitched signals do not require resolution of higher harmonics since their character is amply described by unfiltered results.

In both table 4.1 and 4.2 the amplitude of some partials differs between the pipe metal and steel resonators results. In most cases they occur in high frequency harmonics such as in the 5th harmonic of the 140 Hz result in table 4.1a where the steel resonators' spectrum has a 3dB larger amplitude than the pipe metal one. This is also found in the 10th, 11th and 12th harmonics of table 4.2b . In many cases, however, the steel pipe exhibits slightly lower amplitudes than the pipe metal one such as in the 3rd and 7th harmonics of tables 4.2c and the 5th and 6th harmonics of 4.2d . In each of these instances the steel resonator yields an amplitude 5 dB below that of the pipe metal one.

Non-harmonic partials are found in the 140 Hz results - tables 4.1a and 4.2a.

Steel and Pipe Metal Resonator Comparison

First Run

TABLE 4.1a

140 Hz

			HARMONIC												
			1	2	3	4	5		6		7				
Expt.		filter	FREQUENCY												
								740		895					
8 PR	Pipe	nf	67	46	42	31									
	Metal	+f			41	29	7	13	18	2					
8 PR	Steel	nf	67	46	42	31									
		+f			43	33	12	15	24	2					

TABLE 4.1b

280 Hz

			HARMONIC												
			1	2	3	4	5	6	7	8	9	10	11	12	
Expt.		filter	FREQUENCY												
8 PR	Pipe	nf	73	51	43	42	32								
	Metal	+f				42	31	19	25	16	16	8		8	
8 PR	Steel	nf	72	51	42	40	35								
		+f				40	35	25	26	19	13	7	11		

TABLE 4.1c

560 Hz

			HARMONIC												
			1	2	3	4	5	6	7	8	9	10	11	12	13
Expt.		filter	FREQUENCY												
8 PR	Pipe	nf	64	52	33	34	30								
	Metal	+f				35	32	8	17	16	13	9	7	4	4
8 PR	Steel	nf	63	52	37	33	31								
		+f				35	31	4	20	14	12	9	7	3	2

Steel and Pipe Metal Resonator Comparison

First Run

TABLE 4.1d
1200 Hz

			HARMONIC												
			1	2	3	4	5	6	7	8	9				
Expt.		filter	FREQUENCY												
8 PR	Pipe Metal	nf	61	37	27.5	23	19								
		+f			27.5	22	21	11	16	9	4				
8 PR	Steel	nf	60	37	28	18	19								
		+f			28	17.5	21	8	12	7.5	4				

TABLE 4.1e
2400 Hz

			HARMONIC												
			1	2	3	4	5								
Expt.		filter	FREQUENCY												
8 PR	Pipe Metal	nf	58	38	22										
		+f		40	23	5	15								
8 PR	Steel	nf	58	37	15										
		+f		39	19	16	5								

Steel and Pipe Metal Resonator Comparison

Second Run

TABLE 4.2a
R 140 Hz

			HARMONIC												
			1	2	3	4	5		6		7				
Expt.		filter	FREQUENCY												
								740		895					
8 PR	Pipe	nf	70	41	45										
	Metal	+f			44	28	32	23	27	26	24				
8 PR	Steel	nf	70	43	45										
		+f			44	29	32	25	27	25	25				

TABLE 4.2b
R 280 Hz

			HARMONIC												
			1	2	3	4	5	6	7	8	9	10	11	12	
Expt.		filter	FREQUENCY												
8 PR	Pipe	nf	74	47	47	42	29								
	Metal	+f			46	42	30	19	25	17	16	8	3	9	
8 PR	Steel	nf	75	47	46	41	30								
		+f			47	41	31	22	26	17	16	10	9		

TABLE 4.2c
R 560 Hz

			HARMONIC												
			1	2	3	4	5	6	7	8	9	10	11	12	13
Expt.		filter	FREQUENCY												
8 PR	Pipe	nf	63	55	36	37	28	17	20	18					
	Metal	+f			35	37	28	22	21	23	12	14	6	12	2
8 PR	Steel	nf	62	56	29	37	27	19	15	18					
		+f			30	37	28	20	16	22	8	13	7	12	2

Steel and Pipe Metal Resonator Comparison

Second Run

TABLE 4.2d
R 1200 Hz

Expt.		filter	HARMONIC FREQUENCY 1	2	3	4	5	6	7	8	9
8 PR	Pipe Metal	nf	64	37	33	20	25				
		+f			33	18	24	17	13	13	10
8 PR	Steel	nf	64	39	32	20	17				
		+f			30	21	20	13	14	8	2

TABLE 4.2e
R 2400 Hz

Expt.		filter	HARMONIC FREQUENCY 1	2	3	4	5
8 PR	Pipe Metal	nf	58	37	27		
		+f		38	27	8	3
8 PR	Steel	nf	58	37	29		
		+f		35	29	14	17

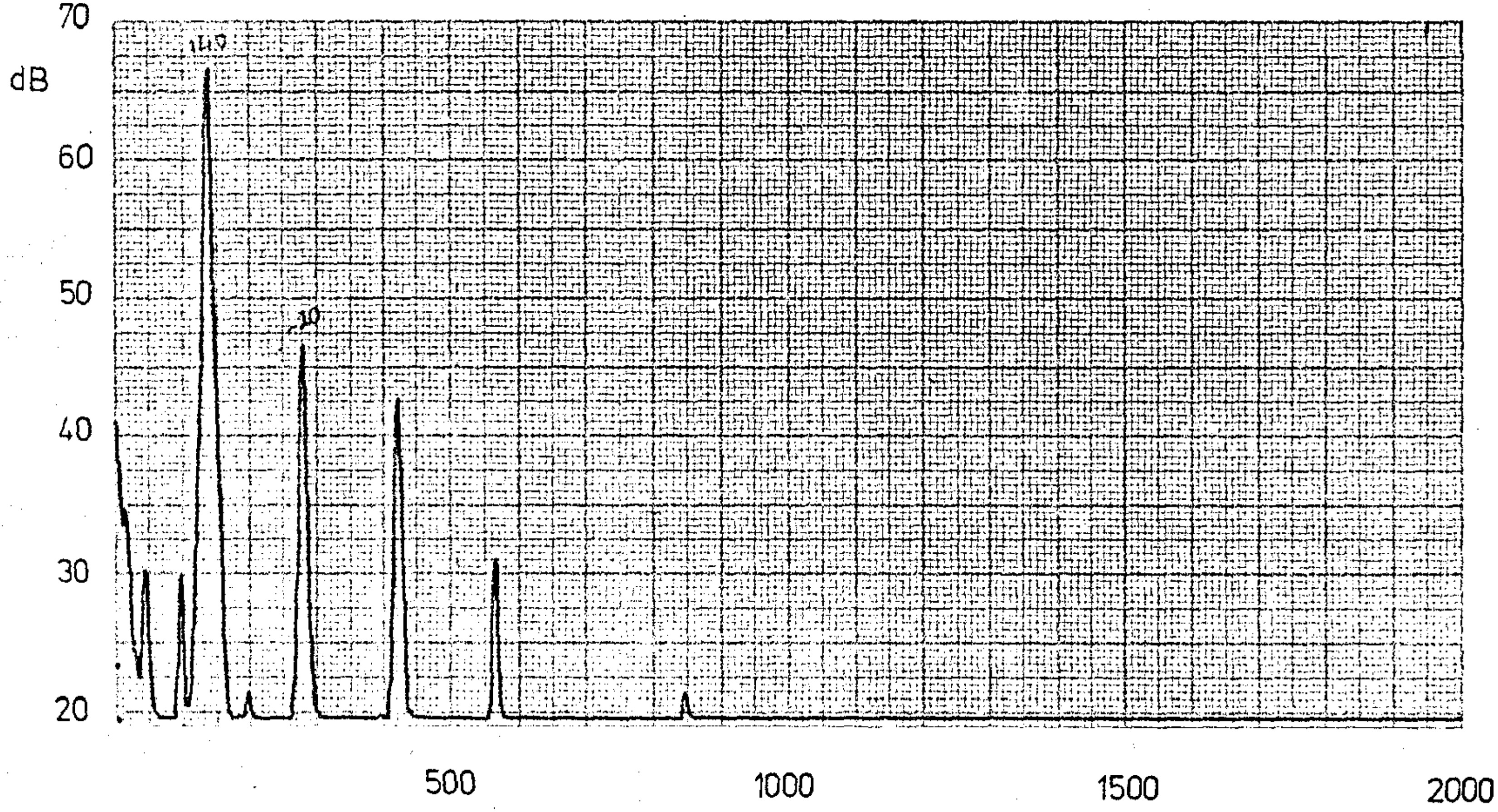

Fig. 4.1a. 8 PR C♯ 140 Hz PIPE METAL

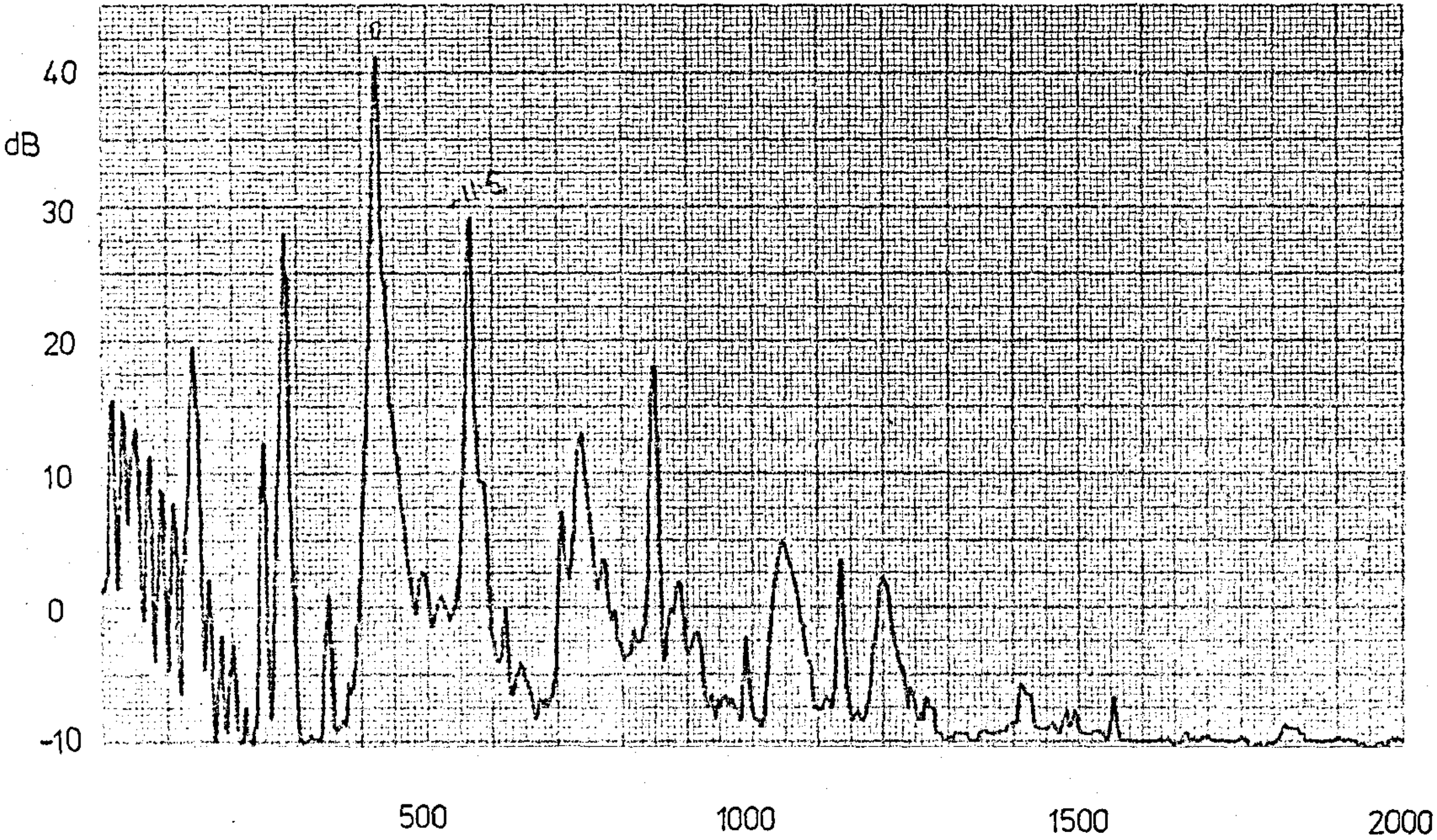

Fig. 4.1b 8 PR C♯ 140 Hz PIPE METAL with 400 Hz Filter.

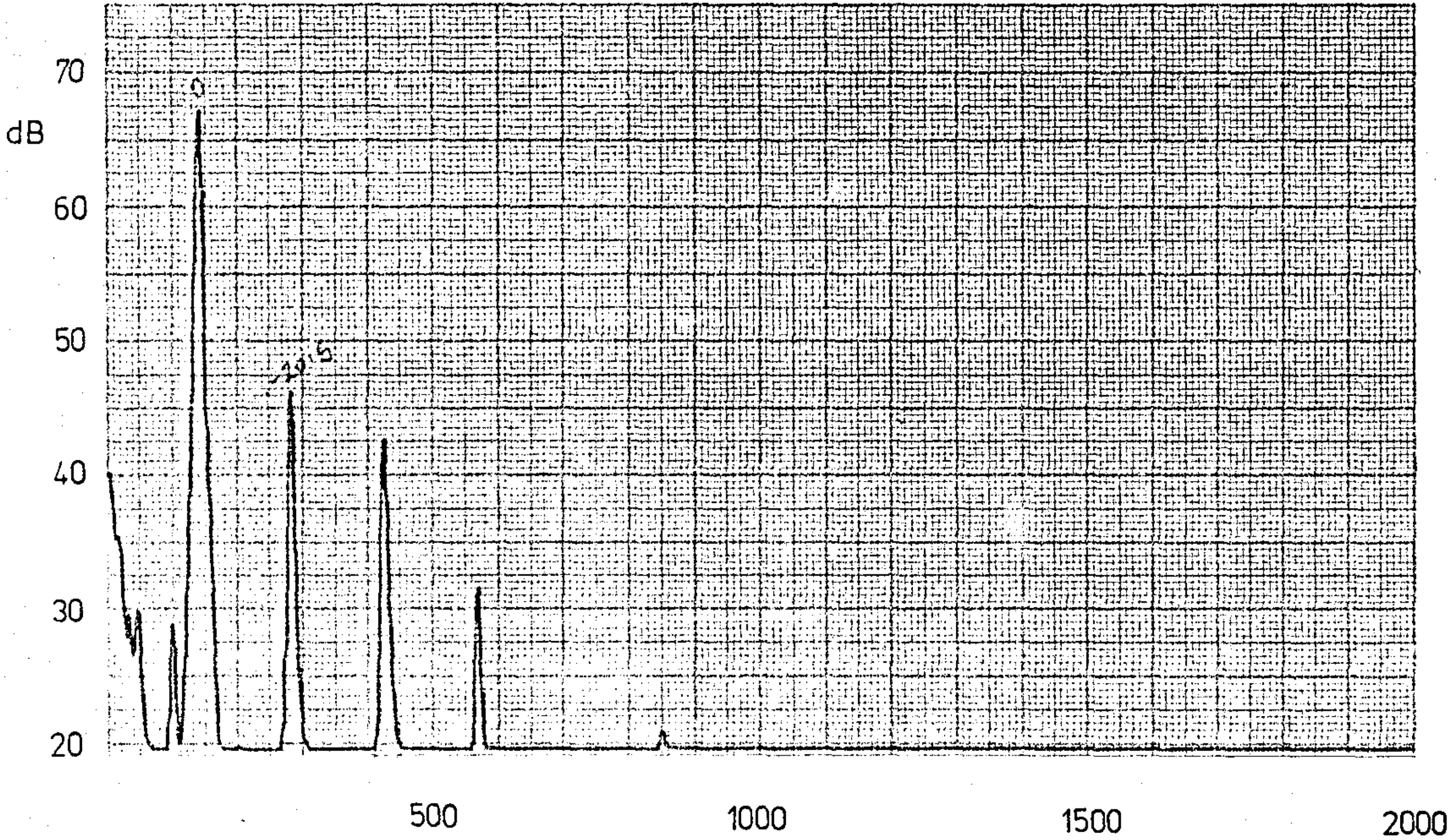

Fig. 4.1c. 8 PR C♯ 140 Hz STEEL

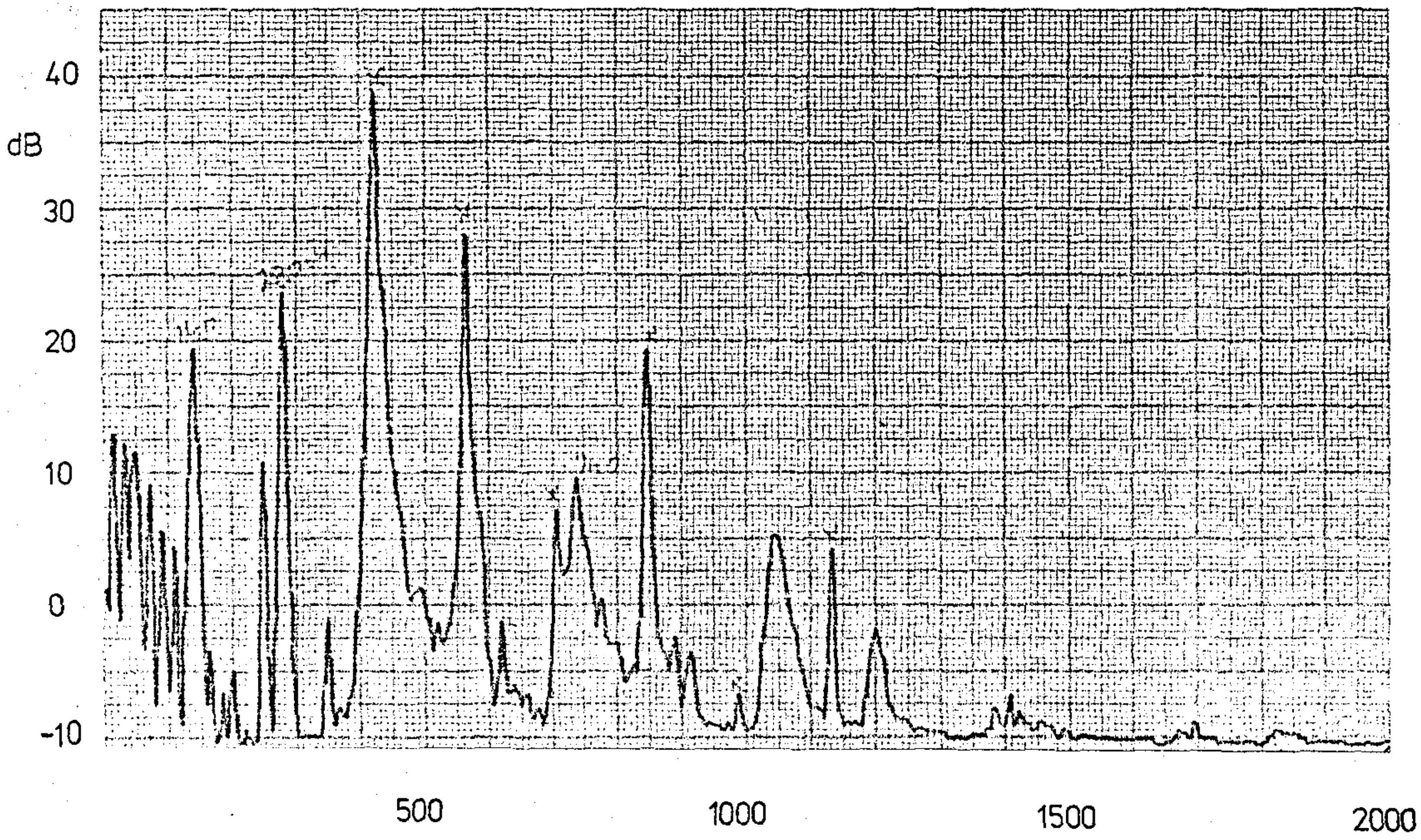

Fig. 4.1d. 8 PR C♯ 140 Hz STEEL with 400 Hz Filter.

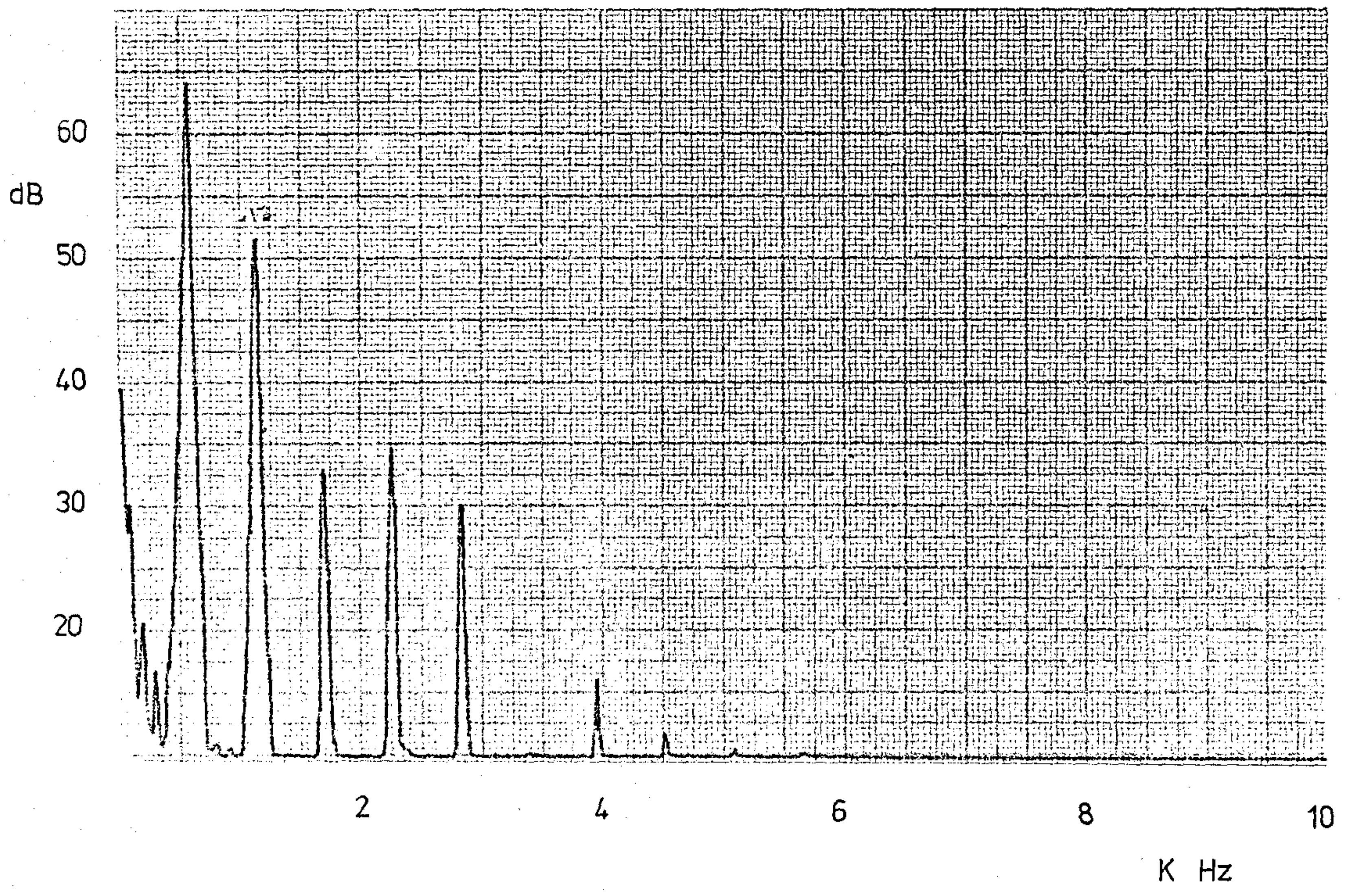

Fig. 4.2a 8 PR 'C♯' 560 Hz PIPE METAL

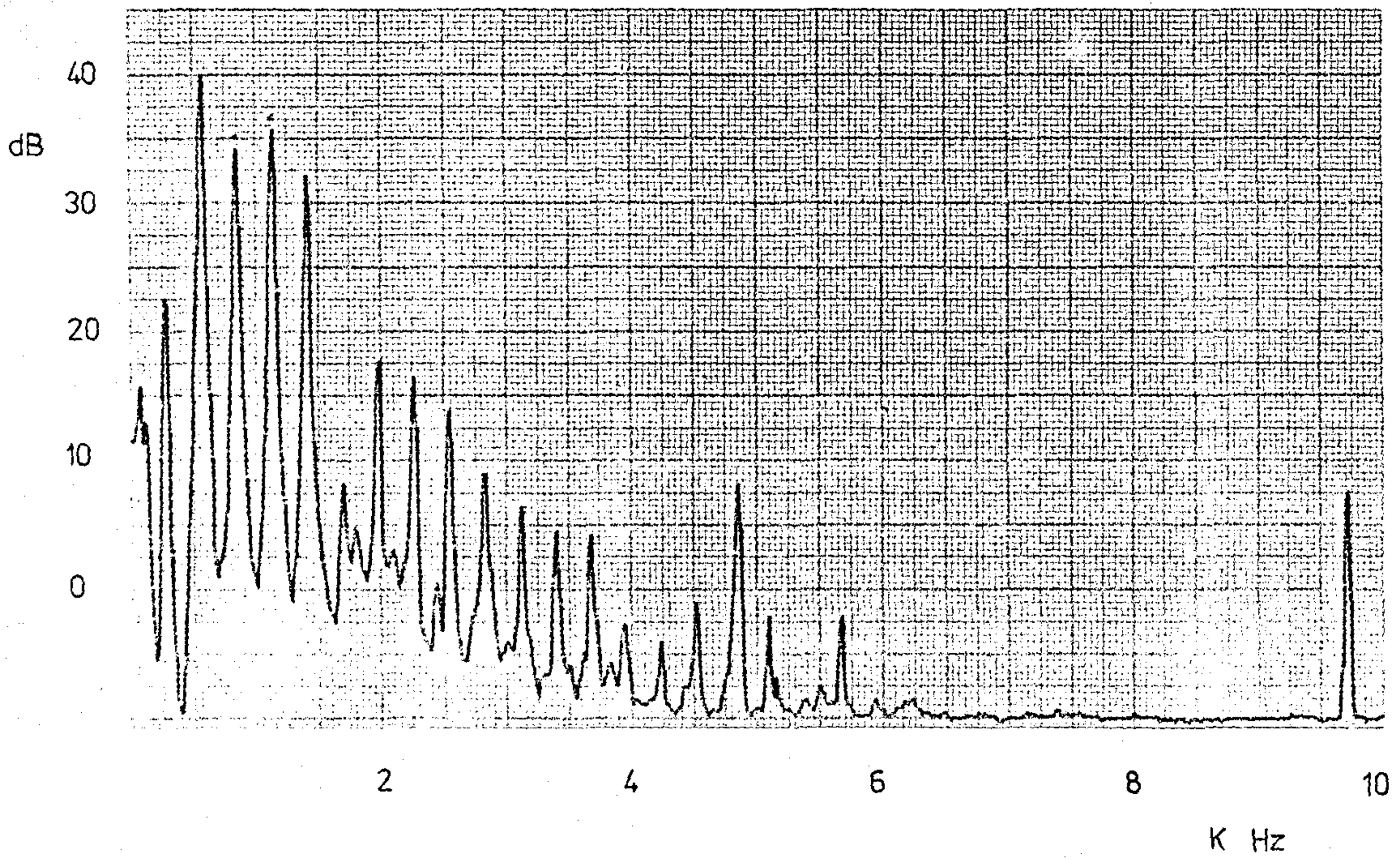

Fig. 4.2b. 8 PR C♯ 560 Hz PIPE METAL with 1400 Hz Filter.

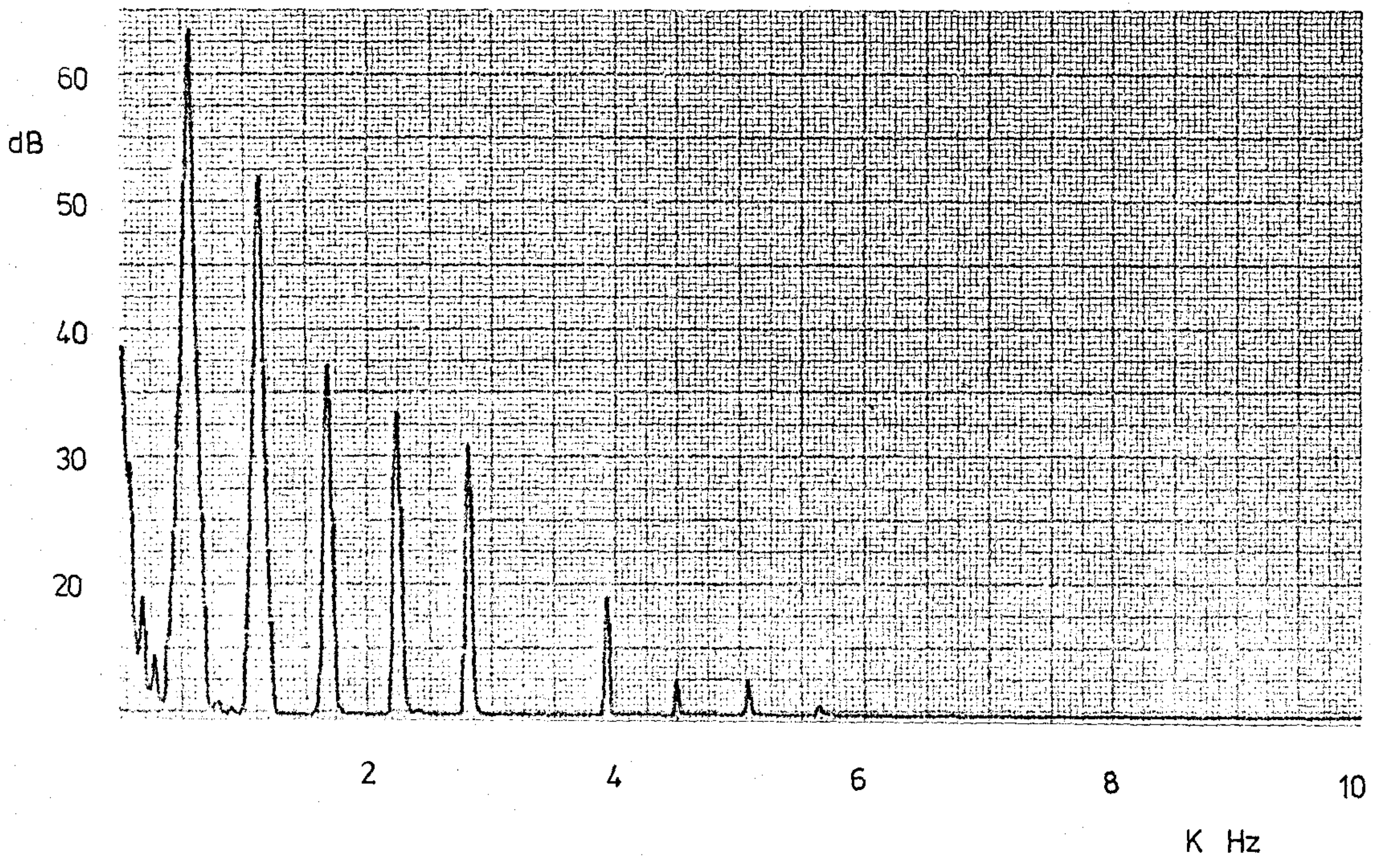

Fig. 4.2c. 8 PR 'C#' 560 Hz STEEL

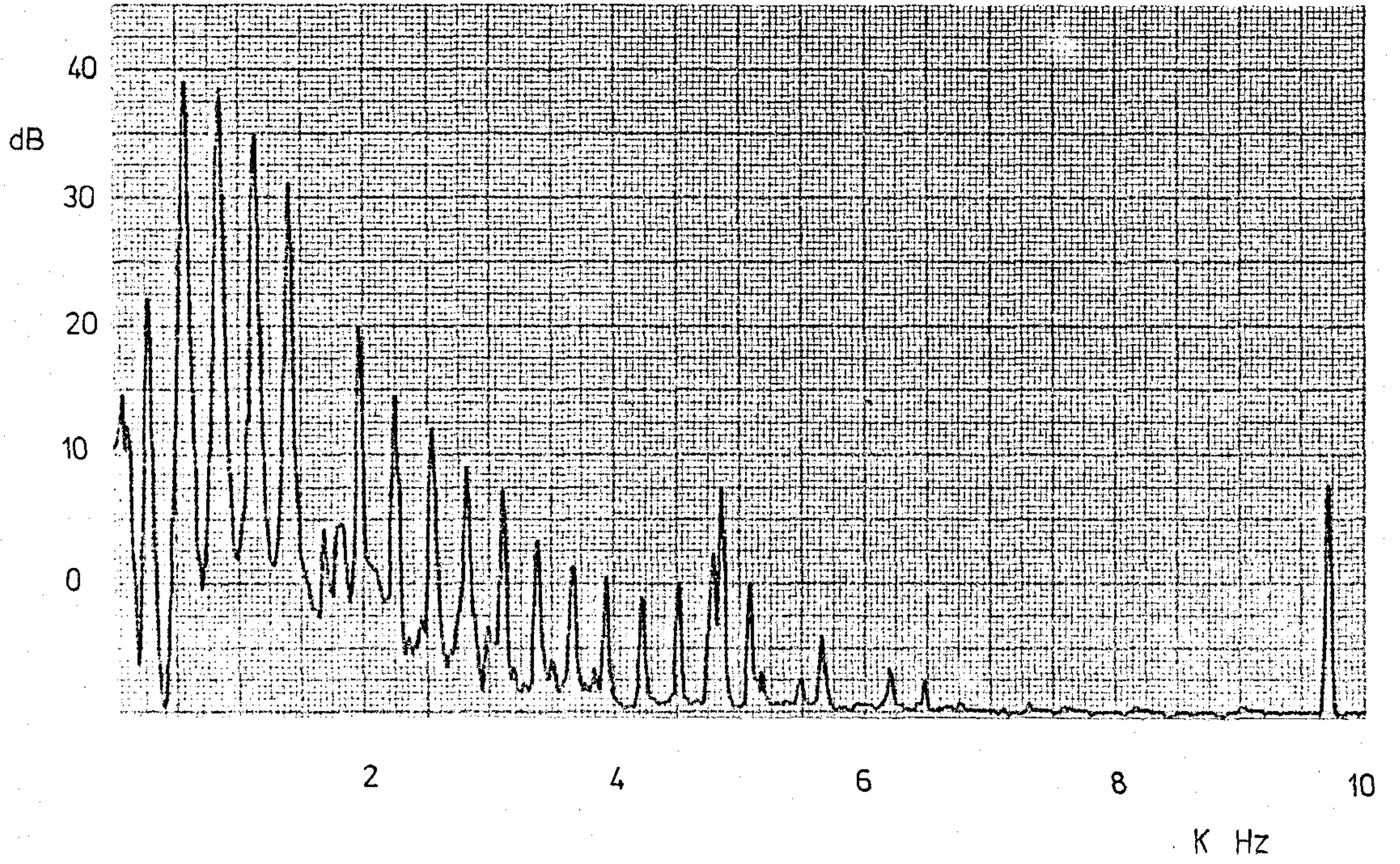

Fig. 4.2d. 8 PR C# 560 Hz STEEL with 1400 Hz Filter.

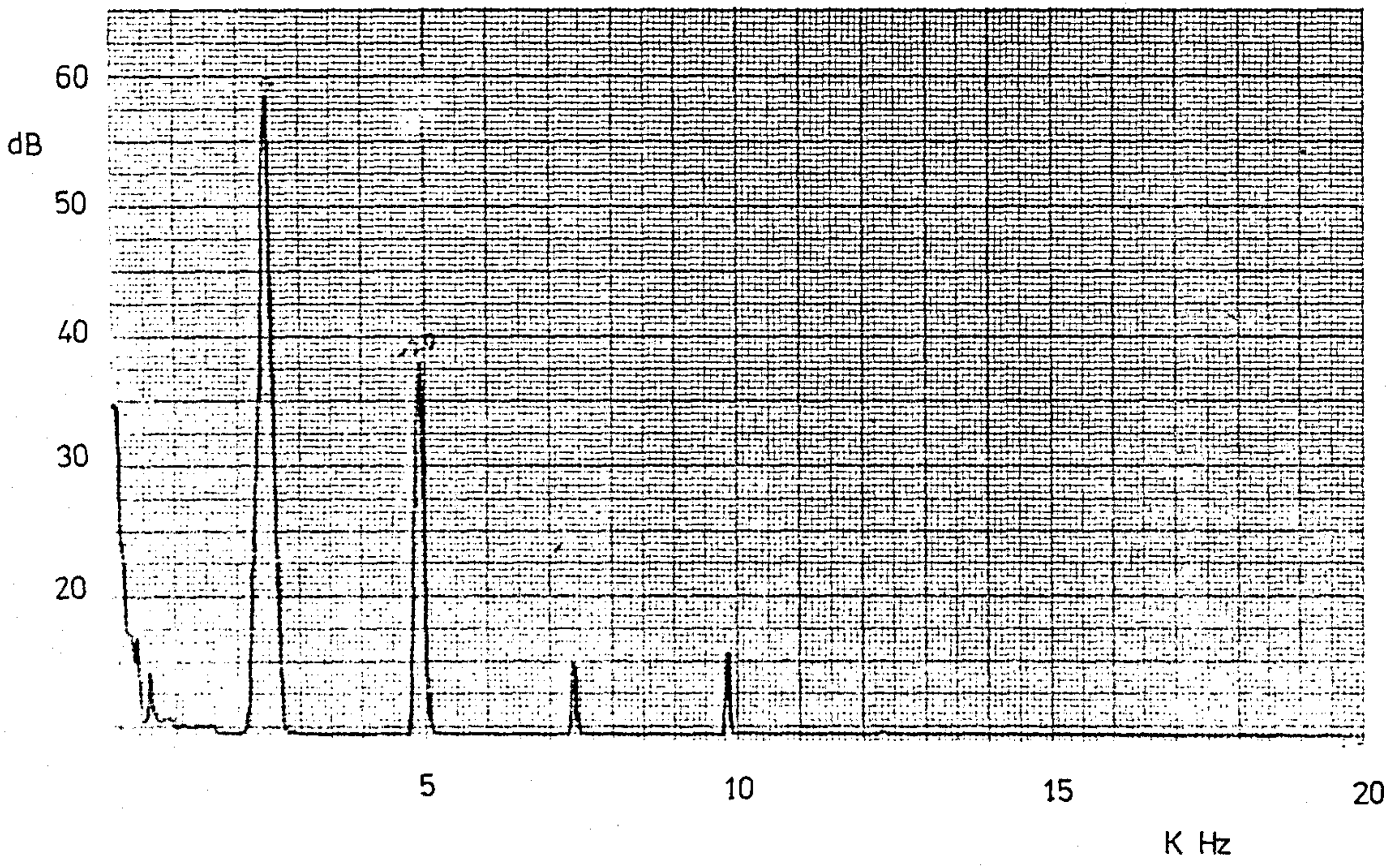

Fig. 4.3a. 8 PR 'C#' 2400 Hz STEEL

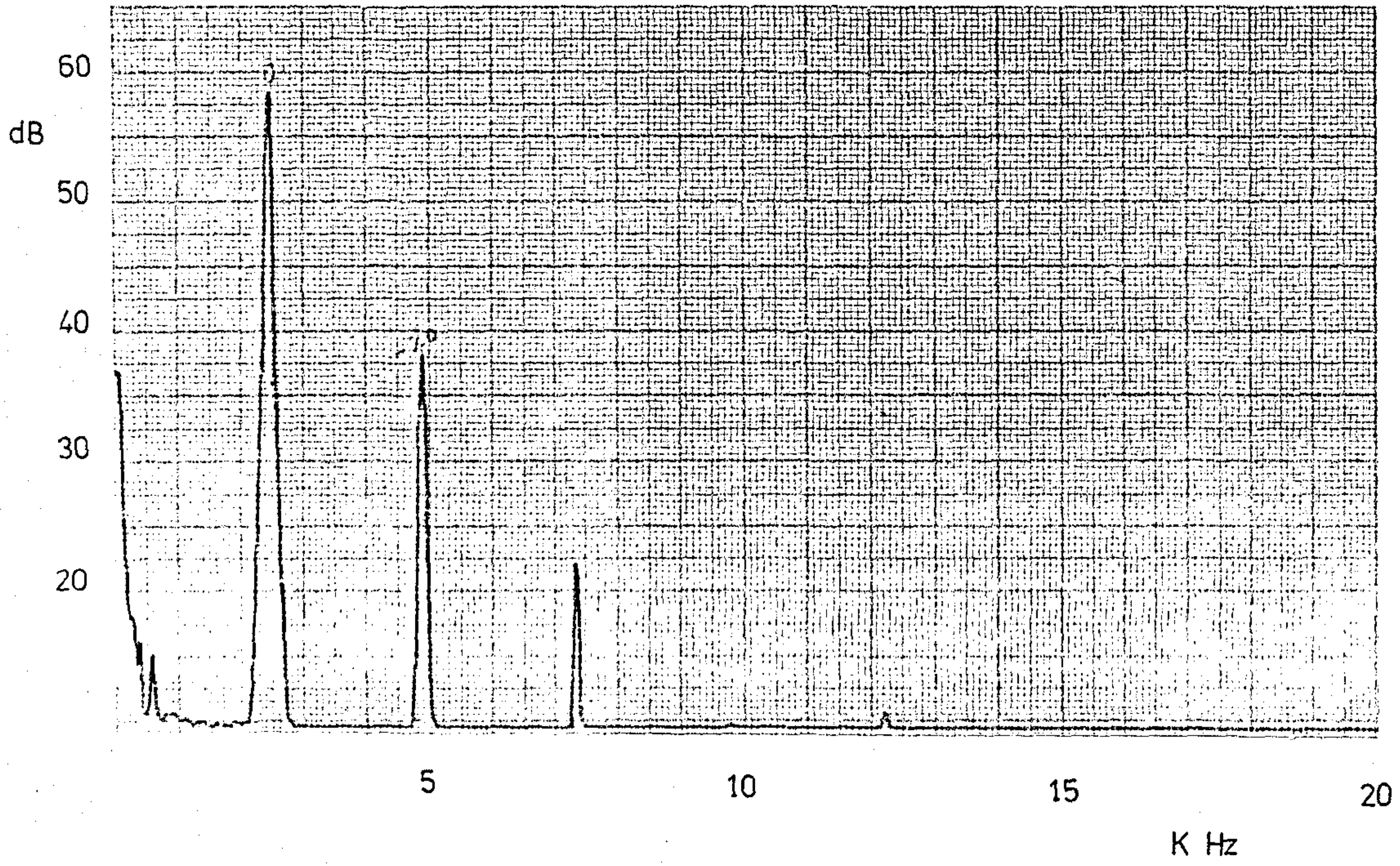

Fig. 4.3b. 8 PR 'C#' 2400 Hz PIPE METAL

4.2.4 Discussion

The 140 Hz results show the similarity of steel (fig. 4.1 c, d) and pipe metal (fig. 4.1 a, b) resonators, although some discrepancies occur they are present only in higher harmonics in the residue region and are unimportant in the aural character of the pipes. The 280 Hz results also contain some changes, though again in the magnitudes of higher harmonics only. In both cases the steel tube's highest partial, the 11th harmonic, having levels of 9 dB and 11 dB, corresponds to a much smaller penultimate harmonic in the pipe metal resonator's spectrum. The latter is followed by a 12th harmonic having levels of 8 dB and 9 dB. Here the changes evident in the comparison of the analysis results if perceptible to the listener would enable the two sounds to be distinguished. As has been shown, high frequency components - in this case above approximately 2,000 Hz, between the 7th and 8th harmonics - are not perceived as individual formants but as the collective component, residue. It is not easy to categorise the influence of a particular component in this part of the spectrum. If the tone consisted only of a 75 dB fundamental and an 11th harmonic, a change of this amount would not be important since a 3080 Hz component would be masked if it was below 20 dB.[1] It seems likely therefore, that modification of this high harmonic would have little effect on the perceived spectra of a complex sound. The 6 dB increase found in the 6th harmonic of this pipe is a slightly different case, since this partial lies in the formant region. This frequency component (1680 Hz) with a SPL of 20 dB could change 1.5 dB before the change could be perceived if this signal was on its own. In the presence of other sounds, the forward masking of the fundamental which is 55 dB above the level of this sound, would minimise the audible effect of this change and infact, it is unlikely that a 5 dB change would be heard. Once again, in assuming the presence of only two components, this and the fundamental, an amplitude of 35 dB would be required for this frequency to be audible. Therefore, as in the first instance of a residue partial, it would appear that the change encountered is of no consequence to the sound stimulus received by a listener.

The 560 Hz results (fig. 4.2) also show good correlation between steel and pipe metal resonators. Slight changes occurred in the non-formant harmonics, but all the components are so very similar, apart from the 5th in the first results, that the two resonators seem to produce the

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[1] Carter and Kryter (21) 72

same tone. As in the previous results, this deviant is a low amplitude component, the discrepancy being between 8 dB for pipe metal and 4 dB for the steel resonator. Compared with the level of the fundamental, 64 dB, this change, although it takes place in a formant component, is of little consequence.

The discrepancies found in the final two pipes, 1200 Hz and 2400 Hz (fig. 4.3), all occur in the residue harmonics. None of them is so large as to have significant bearing on the tone quality emerging from the pipes although it is interesting that the 5 dB reduction in the level of the 4th harmonic in the 1200 Hz results is found, only in the first experiments and not in the repeat. The change in the 4th and 5th harmonics of the 1200 Hz pipe is also worthy of mention though this apparent reversal in the results between the two resonators, as on the first occasion, would not effect the perceived tone.

The results show that whilst changes do occur between the steel and pipe metal resonators considered, the steady tone quality is not changed by these adjustments sufficiently for the pipe's tone to be considered different. This conclusion is similar to that of Backus' study of clarinets.[1]

4.2.5 Summary

The apparent similarity of the steady-tones produced by resonators fabricated in such different materials confirms earlier studies which suggest that changes in steady tone do occur but are insufficient in magnitude to effect the perceived tone of the pipes.

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[1] Backus (2)

4.3 Voicing Experiments

4.3.1 Introduction

Organ pipe voicers are able to adjust the tonal character of pipes by manipulating principally the mouth parts of the pipes. Of particular importance are the adjustments to the position and height of the upper lip, the size of the hole in the pipe foot, the throat width and the position of the languid. The latter's front edge of the languid for instance, and also the edge of the upper lip, may be nicked using a small file to reduce the background noise caused by turbulance in the air passing through the narrow flue.[1] It is proposed to examine the limitations of voicing as a way of changing pipe tone. Primarily, data obtained from this study assists consideration of whether the tone of whole pipes made in non-standard materials might satisfy the voicers sensitive ear. Particular emphasis is placed on understanding the voicers' expectation of the materials and aligning empirical truths with those of theoretical acoustics.

4.3.2 Approach

Information is sought about the extent of the changes which may occur due to voicing adjustments on organ pipes as well as the value of voicing as a method of achieving similar sounds from pipes constructed from dissimilar materials. Experimental work was done in three stages. First, the extent of tonal changes due to simple voicing changes, secondly, a comparison of two geometrically similar pipes fabricated in different materials, and finally the role of pressure transients on onset tone was considered.

4.3.3 Voicing Experiment 1 - The effect of simple Voicing Adjustments

4.3.3.1 Method

It has been noted previously that subjective terminology hinders serious study in this field. The extent of the changes in this

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[1] Mercer (81)
. Coltman (26)

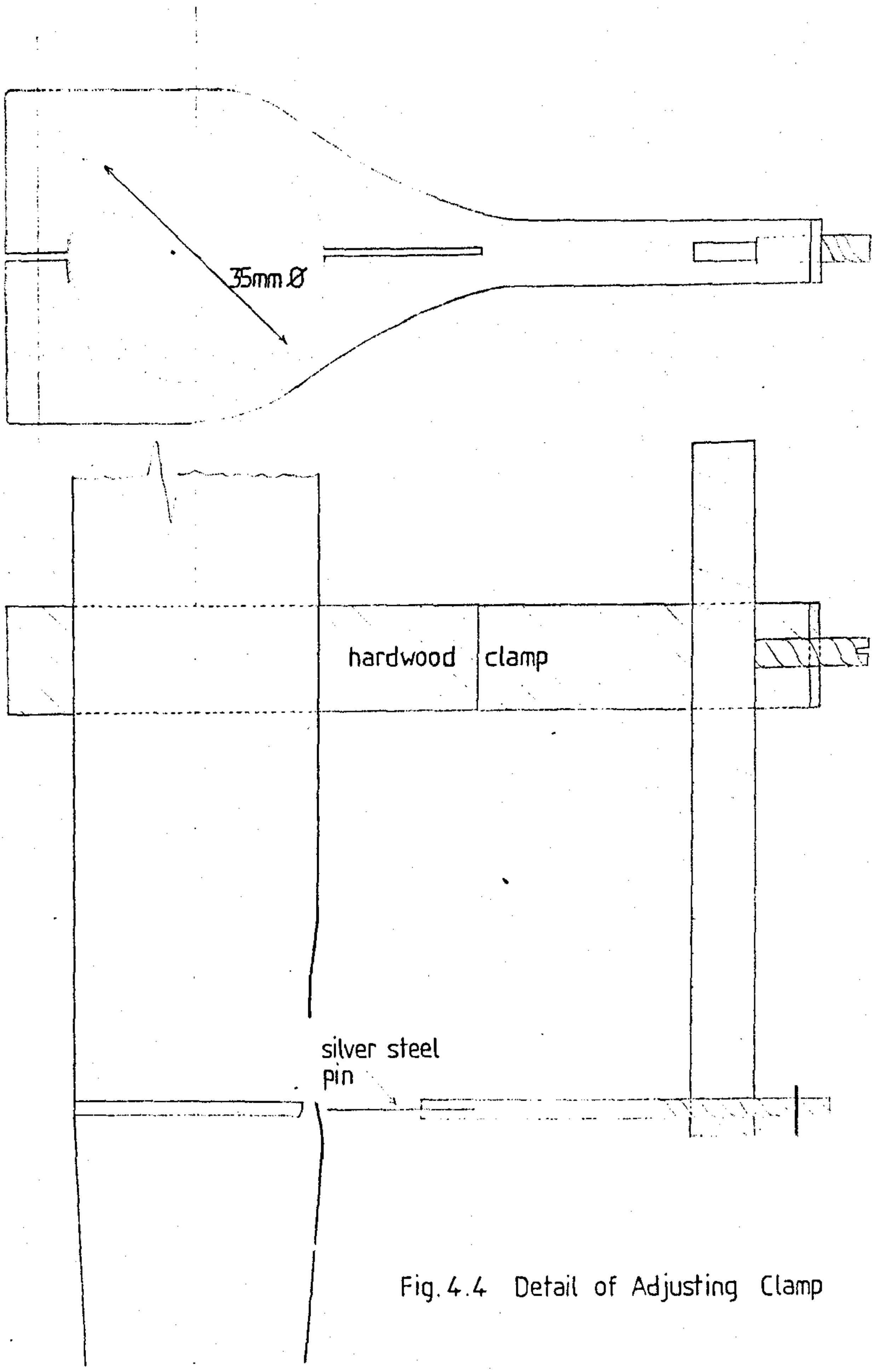

Fig. 4.4 Detail of Adjusting Clamp

experiment are therefore described by comparison with the changes noted in the previous experiment, section 4.1 .

A pipe with a speaking length of about 500 mm and a fundamental frequency of 220 Hz was chosen and the effects of two simple voicing adjustments, moving the upper lip and the ears of the pipe, was studied to show the extent of the tonal changes possible. A clamp was constructed in hardwood which fitted over the pipe resonator 60 mm above the upper lip as shown in fig. 4.4. In this position the clamp did not obstruct the airflow in the sensitive region around the mouth. The clamp, together with a vertical bar through which passed a threaded silver-steel rod with a 1 mm silver-steel pin in its end, was firmly attached to the pipe. The pin was used to vary the position of the lip, adjustments being made with a screwdriver in a slot at the threaded end, where also measurements of the distance the pin had advanced were made with a micrometer.

The experimental method involved steady-state analysis of the pipe unencumbered and then with each part of the jig attached in order to make sure that changes were the result of the adjustments and not of the jig's presence. The effect of constraining the vibrations along the pipes' length by fitting the wooden clamp were also investigated in this way.

4.3.3.2 Results

Expt.			1	2	3	4	5	6	7	8	9	10	11	12	
VE 1	Un-cut Pipe	nf	68.5	54	48	40	28.5								
		+f				38	29	18	26	12.5	13	12	-1	2.5	
VE 2	+ Clamp	nf	68.5	53	48	40	27								
		+f				40	28	18	27	15	17	12	+2	3	
VE 3	+ Pin	nf	68	52.5	48	43	25.5								
		+f				37.5	26	14.5	25.5	11	14.5	11.5	0	2.5	
VE 4	Upper Lip + 0.4 mm	nf	72	57	43	37.5	26.5								
		+f					26	14	25	10	14	11	0	2.5	
VE 5	Upper Lip + 1.8 mm	nf	67	59	30	42.5	27								
		+f				37	28	14	25	8	15	10	0	2.5	
VE 6	Ears	nf	67.5	58	51	52.5	41	38	27.5	24.5	22.5	26.5	24	24	
		+f													

TABLE 4.3
Results of Voicing Experiment 1.

The results of this experiment are shown in Table 4.3 . Other than the result of experiment VE6 in which the pipes' ears were moved, the other experiments show changes principally in the amplitudes of the lower harmonics. The experiment VE4 in which the lower lip was first moved, the fundamentals' amplitude is increased by 5 dB. The second harmonic is similarly increased in this and the experiment VE5 wherein the upper lip was moved further. The 3rd harmonic in these experiments decreased in amplitude, in experiment VE5 by over 15 dB. The remaining harmonics change comparitavely little. Moving the pipes' ears increases the higher harmonics, the 6th, 11th and 12th harmonics over 20 dB.

4.3.3.3 Discussion

The clamp's presence on the pipe had no important effect on the spectrum and even the pin against the upper lip produced only very slight changes. However, the results show the significant changes produced by a 0.4 mm adjustment to the position of the upper lip, and the effect when it is pushed in a further 1.4 mm. It is interesting that significant changes occur only in the lower order harmonics. The first movement of the lip caused a 4 dB increase in the level of the fundamental, 3 dB in the second harmonic and the attenuation of the 3rd and 4th by 5 dB and 6.5 dB respectively. The 1.8 mm change saw the fundamental attain once again its original magnitude, the second harmonic increased a further 2 dB and the 3rd fell to 18 dB below the original value. These amplitude changes are significant in comparison with the changes which occurred in the last experiment, where resonators of pipe metal and steel were compared. More striking changes were produced by moving the ears 1mm inwards. Here the levels of the low order components remained constant compared with the increase in the level of the higher harmonics.

4.3.3.4 Conclusions

Several points emerge from this experiment which are pertinent to the study. First, the results suggest the unimportance of wall vibrations to the steady tone due to the similarity of the pipe tone when the clamp was attached, which agrees with the theoretical finding of Backus and Hundley.[1] The experiment also gives justification, because of the little change produced when the pin was pressed against the lip, for the idea that vibration of the lips also has little influence on tone. Primarily though, the experiment demonstrates the sensitivity of the pipe to even slight physical manipulation of the mouth or lips.

[1] Backus and Hundley (3) - see also section 4.3.1

4.3.4 Voicing Experiment 2 - The effect of Voicing on pipes of similar geometry but Different materials

4.3.4.1 Method

To establish if voicing is a means of achieving desirable sounds from pipes irrespective of the material from which they are made, two similar organ pipes were examined and an attempt made to voice them similarly. The experiment involved a skilled voicer as well as a practiced metal-hand and would have been impossible without this help.

The materials from which the pipes were made are pipe metals containing different amounts of tin. Thus a comparison is made between materials which are different but sufficiently similar to be handled with the same precision and which were of course familier to the craftsmen. One pipe was made in 70 percent tin metal, the other in 30 percent tin with the exception in each case of the languid which was in both instances made from 10 percent tin alloy. These represent extremes in the range of pipe metal normally used in organ building. Diapasons are usually made in the richer tin alloy, flutes in the other. The pipes were made to similar specifications by the same metal hand and the scale employed was that for a Diapason rank with the upper lip scribed into the metal. Both sheets of metal had been cast for several years and were fully anealed. The dimensions of the finished pipes were:

	70 pc Tin	30 pc Tin
Resonator Length	282 mm	282 mm
Internal Diameter	24.7 mm	25.15 mm
Wall Thickness	0.65 mm	0.78 mm

The internal diameters and wall thickness were measured by the metal hand using the rule of thumb techniques associated with the craft, and as can be seen, are not precisely similar. The following brief discussion of the implications of this enables several important points to be made about organ building practice and the tonal manipulation associated with adjustments. Although the internal diameters are slightly different, they are well within the tolerances expected since, according to pipe scales,[1] the diameter of the pipe neighbouring a 25.06 mm

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[1] Rushworth & Dreaper - see acknowledgements

diameter pipe is 24.00 mm. The 70 per cent tin pipe has thinner walls than the 30 per cent tin one but reverting once again to pipe scales, it is found that wall thickness increments for pipes of this size are given for every fourth pipe and therefore pipes of the wall thickness found here would stand adjacent on a windchest. The voicer is able to achieve appropriate sounds from both pipes; the difference in wall thickness not producing a perceivable change in tone quality. The pipes are therefore considered dimensionally similar. It is apparent that the wall thickness increment's effect on tone is taken up by the voicing adjustments performed, otherwise the system of cutting several different pipes from a sheet of a certain thickness could not be adopted. Tonal changes due to slight variations in pipe diameter too appear to be dissipated by this operation.

The aim of the voicing process was to achieve similar tones from both pipes. After fabrication, the pipes were left four weeks to allow the stress produced in working the metal to be relieved by air annealing, leaving the metal pliable without springiness before the voicing proceeded. Each pipe stood on 60 mm Wg of air in a voicing cubicle at 68 degrees F. A considerable time was spent voicing the pipes.

4.3.4.2 Results

Figures 4.5a and 4.5b are respectively steady state graphs of the results from the analysis of the 30 per cent and 70 per cent tin pipes. In figures 4.6a and 4.6b the onset analysis of these signals is presented.

The steady state analysis shows great similarity between the pipes other than in the levels of the 2nd harmonic which is 6 dB larger in amplitude in the results from the 70 per cent tin pipe than in the 30 per cent one. A listening test which involved the skilled ear of an organ builder found that no difference could be detected in the steady sounds of the pipes thus confirming the results of the experiments in section 4.2 .

The results of the onset analysis of these pipes reveals changes in the behaviour of the fundamental and especially the 2nd harmonic. Compared with the 30 per cent tin pipe's onset, figure 4.6a , the onset of the fundamental of the 70 per cent tin pipe is rather slower, reaching its first peak after about 70 mS compared with 50 mS in the former case. The second harmonic of the 70 per cent tin pipe, however, is more rapid, reaching a first peak of similar magnitude to that of the 2nd harmonic after only 50 mS. This then decreases in amplitude by almost 20 dB in

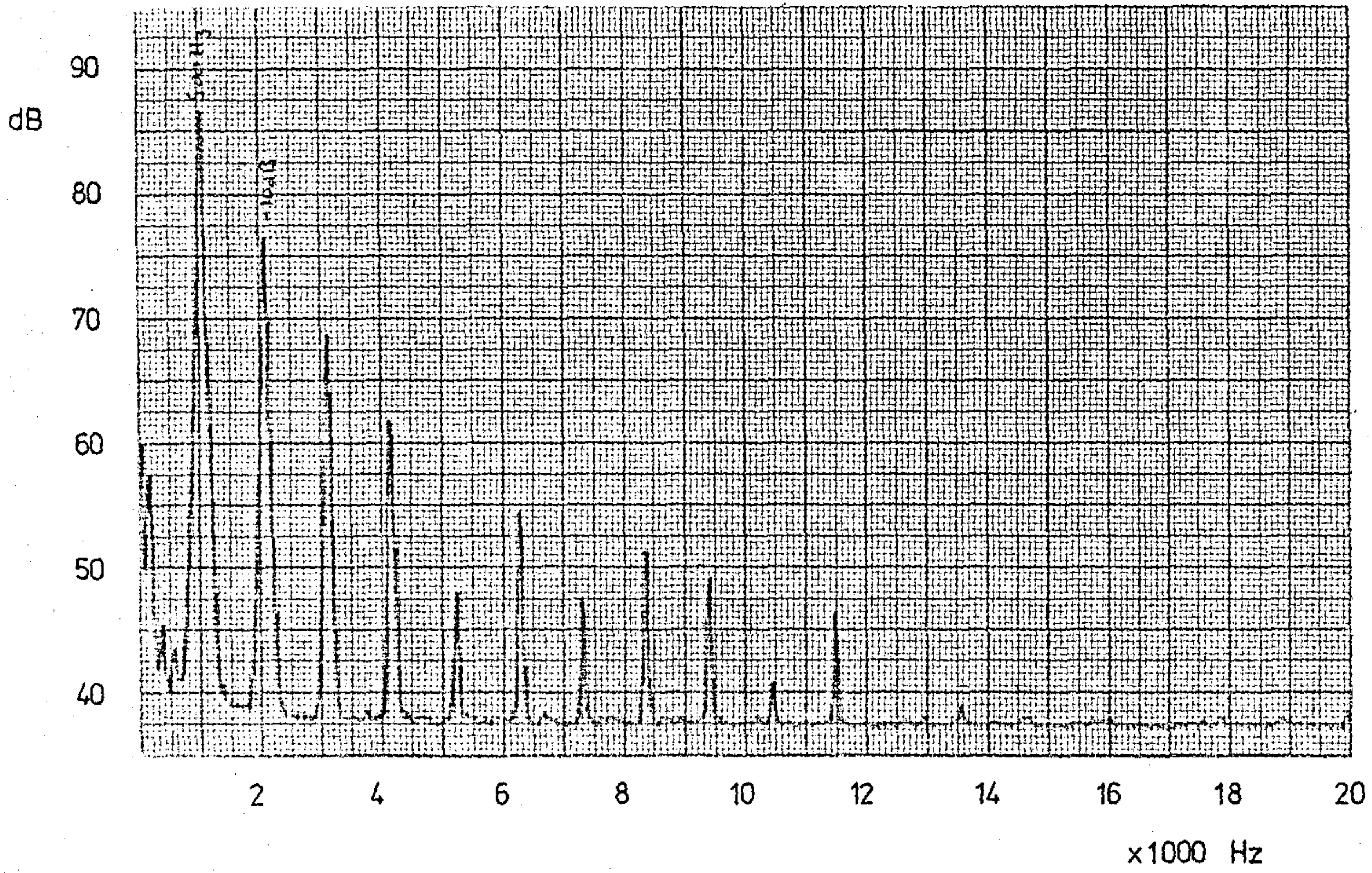

Fig. 4.5a. R+D_1 30% TIN

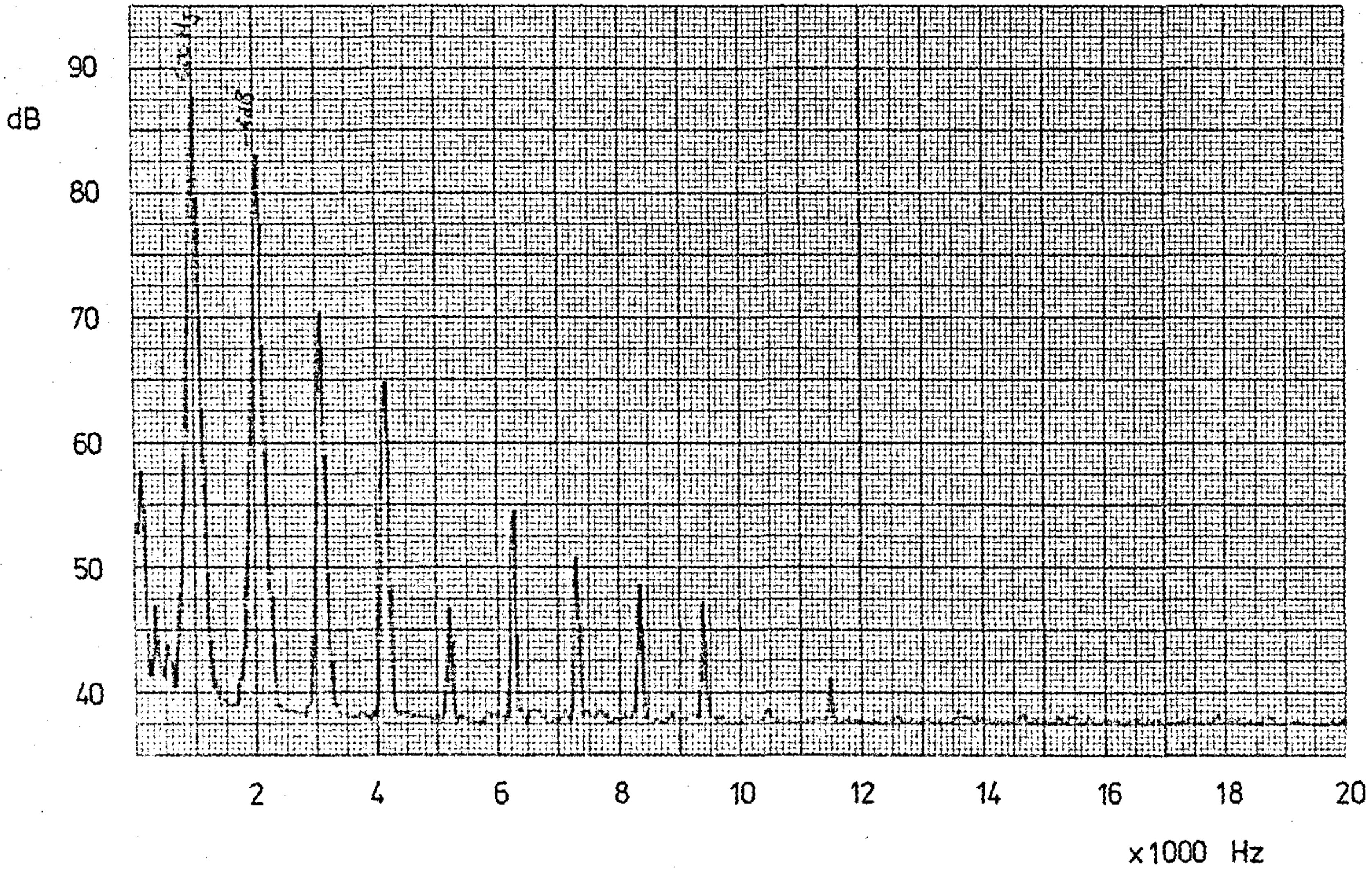

Fig. 4.5b. $R+D_2$ 70% TIN

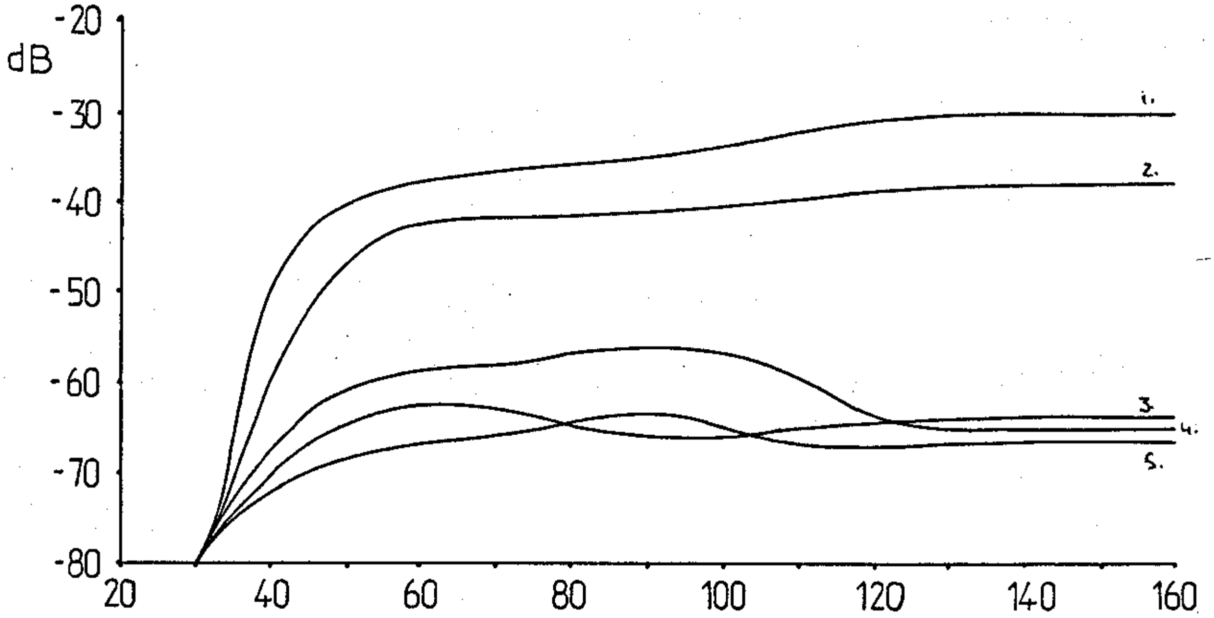

Fig. 4.6a R+D1 30% Tin

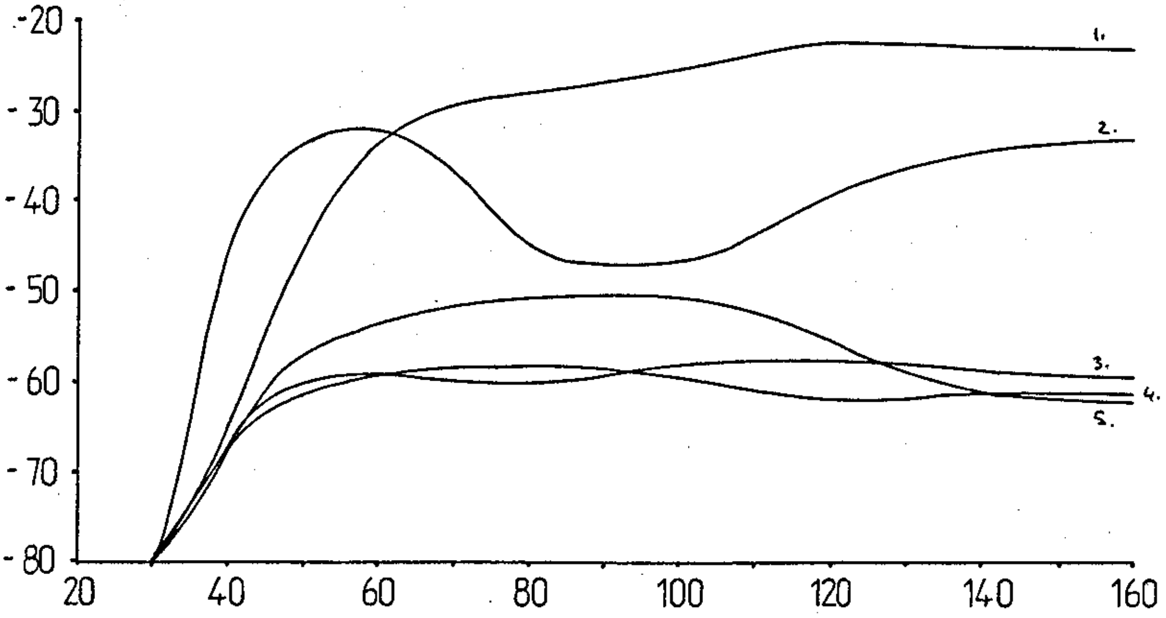

Fig. 4.6b R+D2 70% Tin

the next 40 to 50 mS. This then once again builds up but this time steadily to its final value. The other three harmonics behave similarly in both instances building up rapidly in the initial stages and finally settling to their steady levels after 130 to 140 mS.

4.3.4.3 Conclusions

It was apparent quite early in the process that the 70 per cent tin pipe's onset was brighter than that of the other. The steady state analysis demonstrates that, other than a 5 dB difference in the second harmonic, the pipes are very similar. Hence the difference appeared to occur in the onset of the pipes rather than the steady state. Subsequent analysis of the pipe confirmed this. Time domain analysis shows the overshoot, early in the onset of the 70 per cent tin pipe, which so characterises it. The two pipes could not be voiced to sound the same.

4.3.5 Voicing Experiment 3 -
Pressure-Transients Effect on Tone

4.3.5.1 Theoretical

It has been proposed by H.L. Fletcher[1] that the pressure transient is significant in determining the character of a pipes' onset, plosive attacks producing a characteristic dominant second pipe mode. He provides an equation for determining the character of the pressure transient:

$$P(t) = P_0 + (P_1 - P_0) \exp(-t/\tau)$$

where, P_1 is the pressure peak
P_0 is the steady pressure
τ is the decay time from peak

He suggests that if $P_1 = P_0$, increasing the wind pressure can lead to greater amplitude in the second harmonic during the transient and an overshoot reminiscent of the 70 per cent tin pipe.[2] The effect of wind pressure on the onset of the two pipes used in the voicing experiment was examined.

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[1] Fletcher (40)

[2] Fletcher (40) 229

4.3.5.2 Method

The experiment compares the attack of the 70 per cent tin pipe used in the last experiment with that of the 30 per cent pipe on various wind pressures. Since the envelope shape of the attacks under discussion are easily noticeable, harmonic analysis is not used for the experiment, oscilloscope photographs being used instead. Attack transients of the 30 per cent tin pipe were examined for pressures of 60 mm Wg to 200 mm Wg in 10 mm Wg increments.

Pipes were sounded one metre from a microphone and the trace displayed on the screen of a storage 'scope photographed. At first the 'scope's internal triggering was used but this was found inappropriate because of the loss of vital information about the early part of the signal due to the rapidity of the transients' onset. Triggering was therefore effected using the control device encountered previously in section 4.2.2.1 . The arrangement is shown in the diagram, fig. 4.7 . The wind pressure was varied by controlling the speed of the blower using a Variac transformer and monitored as before using a water manometer.

4.3.5.3 Results

Comparison of the photographs reveals the changes which occurred to the onsets of the pipes. It is convenient to tabulate the results in terms of the time elapsing before the first cycle, the amplitude of the signal at the steady state and, since peaks can be seen in all the transients examined, the amplitudes and time of each peak. The first peak, when present, occurs in the first stage of the onset, before the second peak which marks the overshoot or the first major amplitude. The third peak refers to any amplitudes smaller than that of the steady state subsequent to peak two. The results are tabulated in Table 4.4 .

The onset of the 30 per cent tin pipe on its normal wind pressure of 60 mm Wg begins 20 mS after the pallet valve is activiated and a first peak occurred 20 mS later. 30 mS after this a second peak measuring 120 mV occurred and after a total of 160 mS the steady level of 100 mV was achieved (fig. 4.8). Unlike this pipes' onset, that of the 70 per cent tin pipe on the same wind pressure exhibits a larger peak of 100 mV after 55 mS, followed by a decline in amplitude to 70 mV after a further

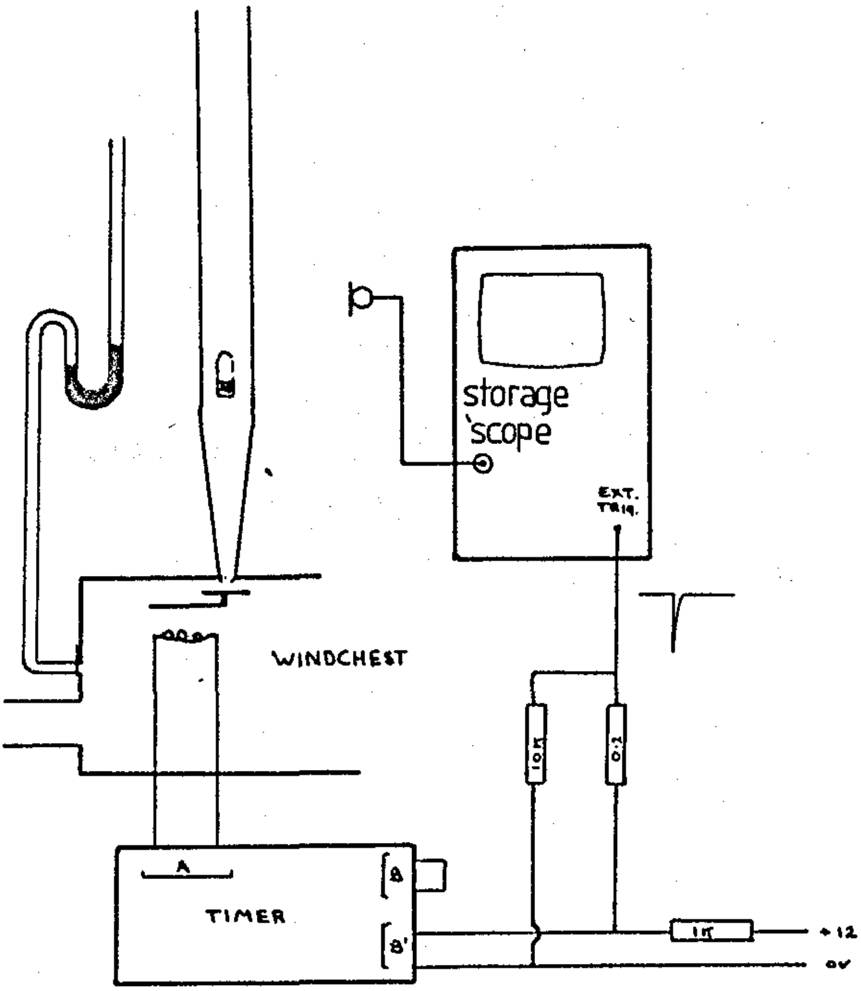


Fig. 4.7 Layout for Pressure Transient Experiment

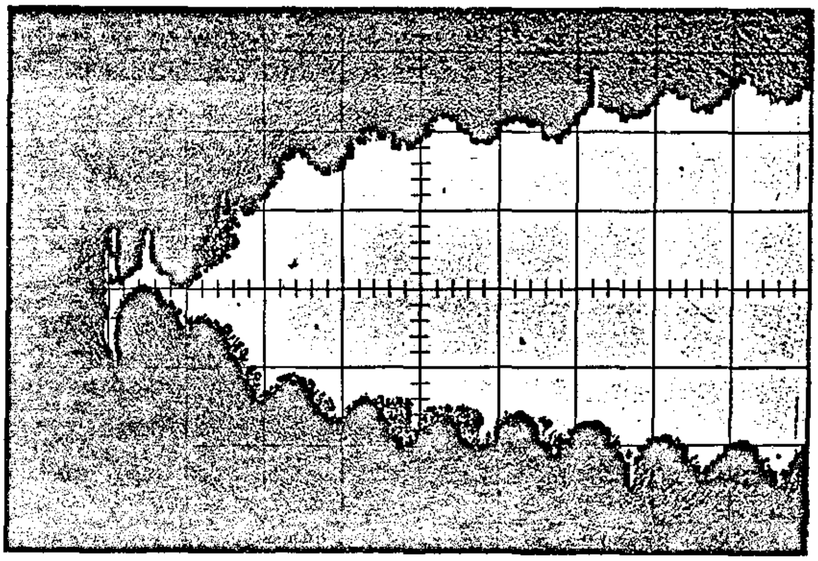
35 mS and a gradual buildup from this level to 100 mV after 180 mS (fig. 4.11). This characteristic onset, here described from oscilloscope pictures, is that described in section 4.3.4.2 after more rigorous transient analysis.

As the wind-pressure beneath the 30 per cent tin pipe was increased the first peak occurred later though its amplitude was little effected. After 90 mm Wg however, this feature disappeared completely: the second peak, which had also progressively occurred later, had become so large in amplitude that the minor first peak is undistinguishable. This is seen in fig. 4.9 which shows the 110 mm Wg photographs. At 130 mm Wg and 140 mm Wg the first peak is discernible and at the later pressure a third peak is found of lower amplitude than either the second or the steady level which is reminiscent of the effect of the 70 per cent tin pipe on 60 mm Wg (figures 4.12a and 4.12b). As the pressure is increased the time before the steady level emerges increases, though in the region 190 mm Wg to 200 mm Wg when the pipes' onset is raucous and quite unstable, the total transient duration appears to fall off slightly from the maximum achieved at 160 mm Wg, 400 mS.

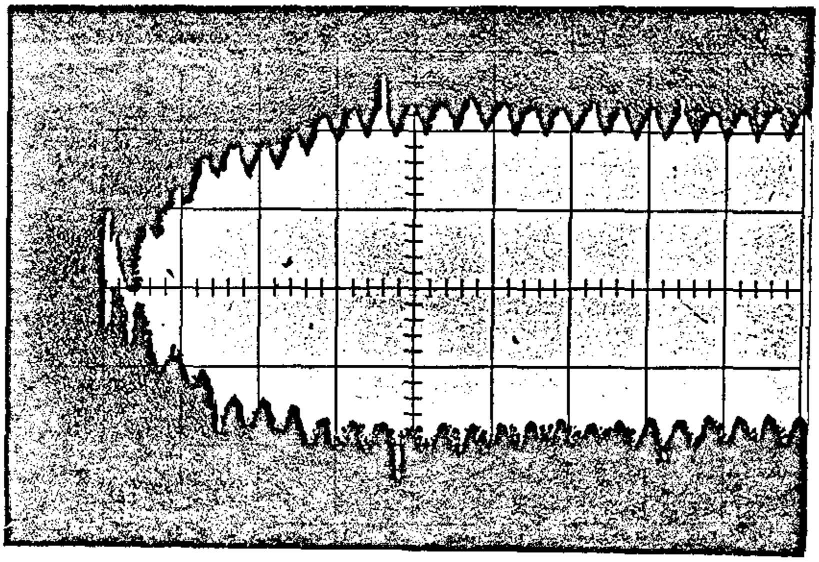
4.3.5.4 Discussion

It is convenient also to consider the results in three sections. In the first section the wind pressure ranges from 60 mm Wg, the pressure on which the pipes were voiced, to 100 mm Wg. As the pressure increases over this range the amplitude of the signal also increases and at 100 mm Wg the amplitude is 2.5 times that of the pipe on 60 mm of wind. This is shown in figures 4.8 and 4.9. Also apparent as the pressure increases is the absence of a clearly defined first peak and the lengthening of the transient period before the steady-state is achieved. When the pressure is increased to 120 mm Wg, as shown in fig. 4.10, the first peak becomes less discernible and the second overshoots 50 mV above the subsequent steady state level. Between the overshoot peak and the steady signal a hallow is noted in the signal from the 70 per cent tin pipe. (fig. 4.11). A similar effect is noted at 140 mm Wg but between this and 160 mm Wg the level of the third peak increases towards that of the steady state again. (fig. 4.12a). In the third section, for pressures above 170 mm Wg, the pipes exhibit increasing instability which manifests itself on the photographs as small bright flecks. (fig. 4.12b).

As predicted by Fletcher, at the point when overshoot occurs the

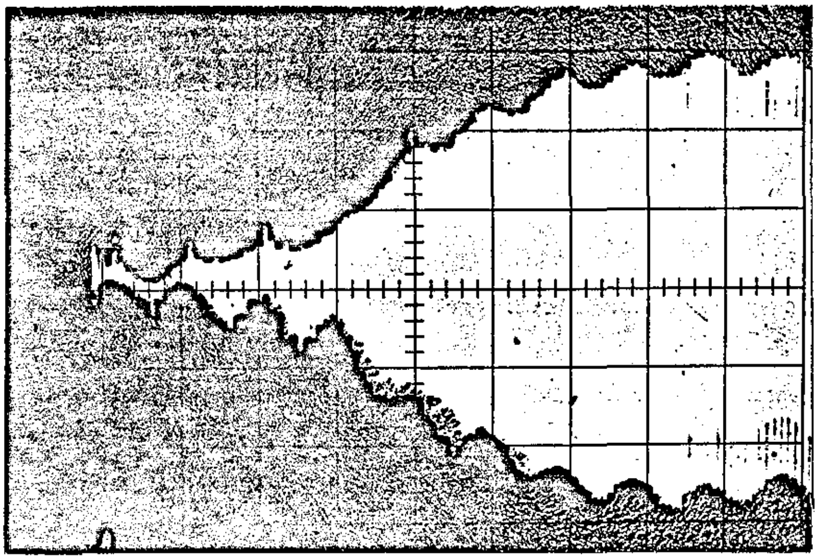


a. 20 mS/Div.

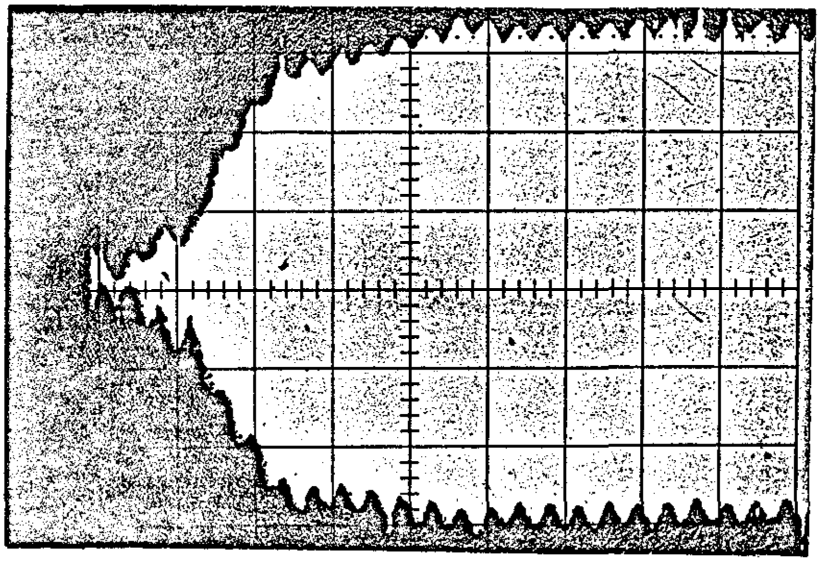


b. 50 mS/Div.

Fig. 4.8 30 % Tin 60 mm Wg.

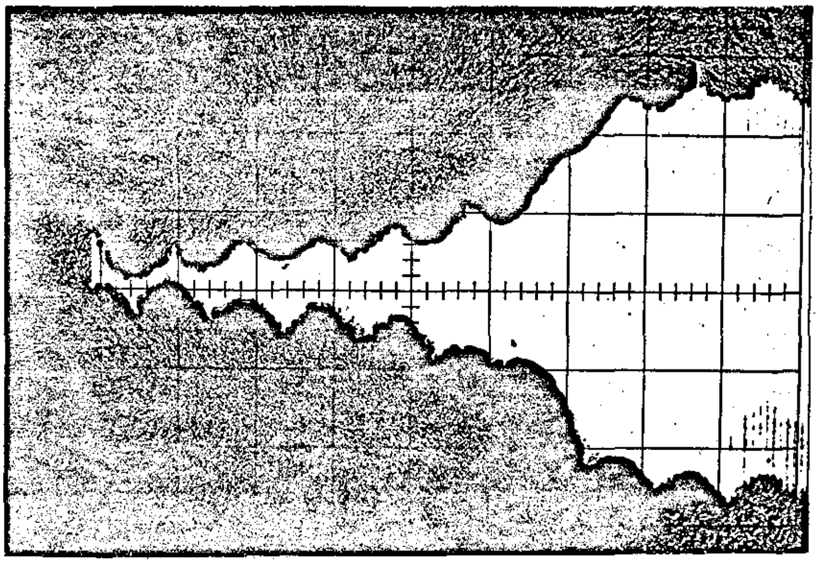


a. 20mS/Div.

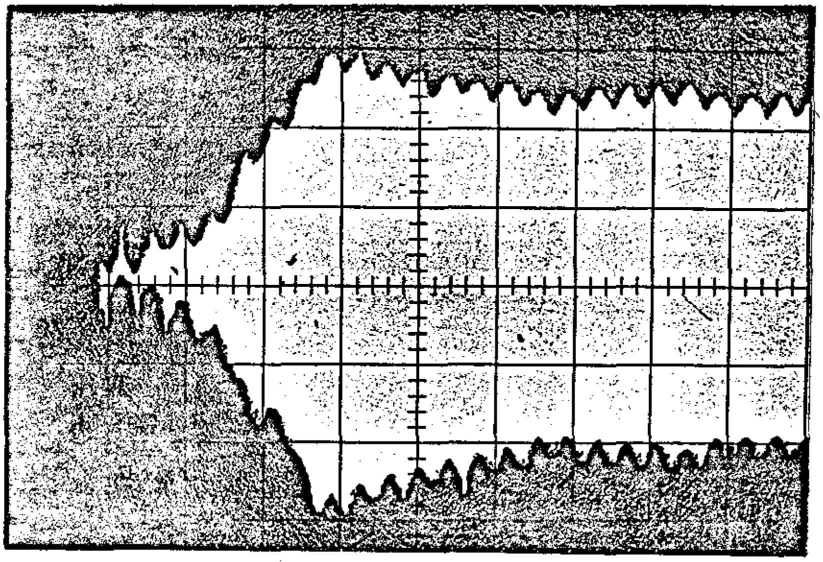


b. 50 mS/Div.

Fig. 4.9 30 % Tin 110 Wg.



a. 20mS/Div.



b. 50mS/Div.

Fig. 4.10 30% Tin 120mm Wg.

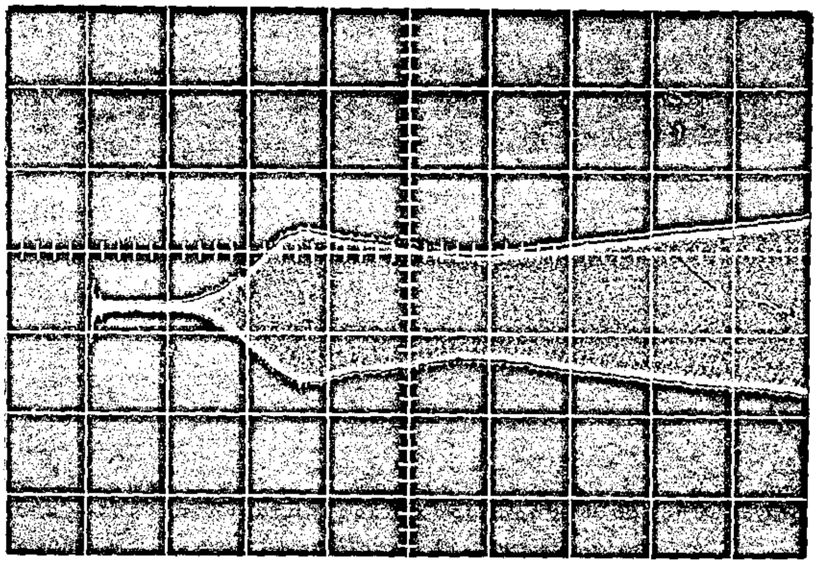


Fig. 4.11 70% Tin 60 mm Wg. 20 mS/Div.

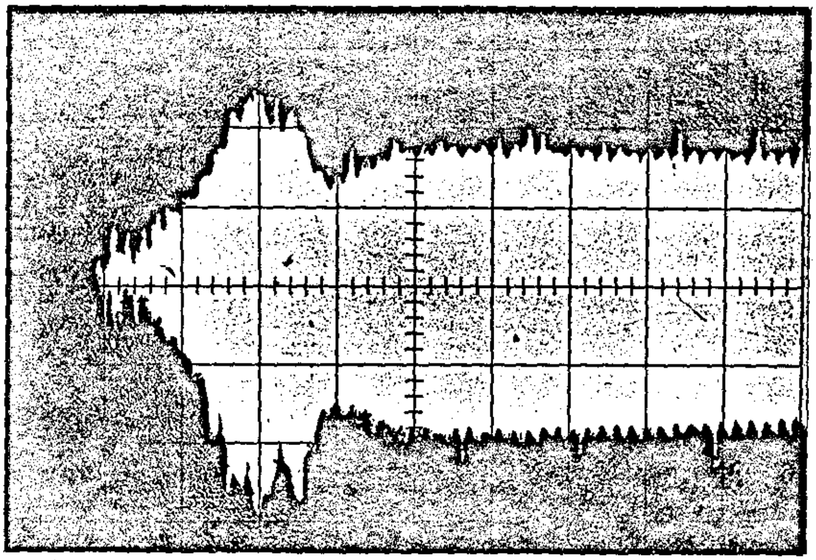


Fig. 4.12 a. 30% Tin 160 mm Wg. 110 mS/Div.

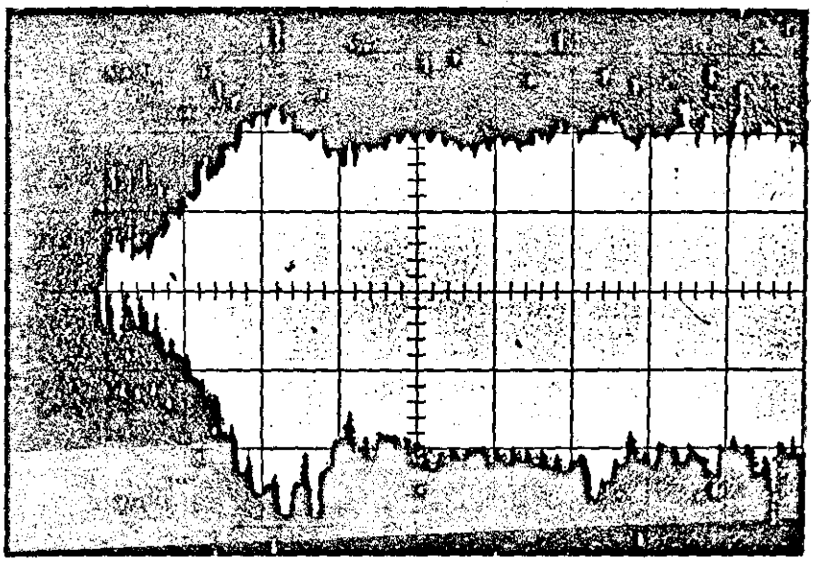


Fig. 4.12 b. 30% Tin 170 mm Wg. 100mS/Div.

Pipe	Pc Tin	Pressure	First cycle	First Peak		Second Peak		Third Peak		Steady State	
			Time	Time	Amp	Time	Amp	Time	Amp	Time	Amp
Flute	30 %	60 mm Wg	20 ms	40 ms	90 mV	70 ms	120 mV	–	–	160 ms	100 mV
		70 mm Wg	20 ms	45 ms	90 mV	80 ms	130 mV	–	–	170 ms	130 mV
		80 mm Wg	20 ms	50 ms	95 mV	80 ms	160 mV	–	–	200 ms	150 mV
		90 mm Wg	20 ms	60 ms	90 mV	100 ms	160 mV	–	–	200 ms	180 mV
		100 mm Wg	20 ms	–	–	110 ms	170 mV	–	–	200 ms	220 mV
		110 mm Wg	20 ms	–	–	120 ms	200 mV	–	–	200 ms	250 mV
		120 mm Wg	20 ms	–	–	150 ms	280 mV	–	–	290 ms	230 mV
		130 mm Wg	20 ms	130 ms	100 mV	170 ms	260 mV	–	–	300 ms	150 mV
		140 mm Wg	20 ms	130 ms	100 mV	170 ms	260 mV	250 ms	110 mV	300 ms	150 mV
		150 mm Wg	–	–		200 ms	260 mV	290 ms	140 mV	370 ms	150 mV
		160 mm Wg	–	–		200 ms	270 mV	300 ms	140 mV	400 ms	170 mV
		170 mm Wg	–	–		230 ms	270 mV	330 ms	150 mV	400 ms	190 mV
		180 mm Wg	–	–		200 ms	250 mV	420 ms	150 mV	400 ms	210 mV
		190 mm Wg	–	–		150 ms	160 mV	210 ms	130 mV	350 ms	190 mV
		200 mm Wg	–	–		150 ms	200 mV	200 ms	120 mV	250 ms	150 mV
Diapason	70 %	60 mm Wg	20 ms			55 ms	100 mV	90 ms	70 mV	180 ms	110 mV

TABLE 4.4 Tabulated Results of Pressure Transient Experiment

total SPL is much larger than for a pipe on normal pressure. However, the onset duration is also vastly elongated becoming almost twice that of the original pressure when it is raised to 140 mm Wg. As the pressure is raised and the pipe becomes unstable, the transient duration becomes shorter. At the point of maximum overshoot and greatest similarity to the richer alloy pipe (160 mm Wg) the onset duration is at its largest. The increase in transient duration due to greater wind pressures makes it impossible for similar tone quality to be elicited from pipes fabricated in pipe metal alloys rich in lead as is produced from pipes made in alloys richer in tin, although it is possible to produce an overshoot in their onset transient reminiscent of the predominantly tin pipe by this adjustment.

4.3.6 Discussion of Voicing Experiments

The three voicing experiments have demonstrated the pipe voicer's inability to produce similar tone quality from the two pipes, the extent of the changes produced by manipulation of the pipe's mouth and the radical effect of wind pressure changes, which suggests that the voicer's control of the pipe's tone is more restricted than was surmised from the survey of literature. The voicer certainly brings to his work a great amount of skill and artistry but, are the voicing adjustments which effect vast changes on pipe tone used only to order the varied noises of unvoiced pipes, and is the effect of the subtle adjustments strictly limited within the bounds of this condition?

Justification that the tone quality available from a pipe which can be regarded as musical is small in comparison with the range of sounds which can be elicited from the pipe is gained from this, the final paragraph of M. McNeil's recent study:[1]

" The steady-state timbre most desirable to the author is not too rich, as this will mask harmonic development in other stops, nor can any of the harmonics or groups of harmonics stand out within a single pipe. Just as single loud solo stops destroy the chorus of many other stops, so do loud individual harmonics destroy the 'chorus' of subtler harmonics within the single pipe. "

He implies that the timbre most desirable involves radical

[1] McNeil (77) 11

curtailment of the pipe's harmonic spectra, thus the wide range of sounds possible, demonstrated in 4.2.3 , is not suited to the musical purpose for which pipes are made. The extent of the tonal range exhibited in experiment 4.2.4 is therefore restricted, the voicing adjustments being unable to modify the tone substantially enough within the limits of musicality. Clearly then, voicing involves not only controlling the tonal spectra of pipes but reducing the wealth of overtones either present in the unvoiced pipe or extricable by careful adjustment, to produce sounds which will combine well.

A theoretical justification for this is found in N.H. Fletcher's, "Sound Production by Organ Flue Pipes."[1] Having stated that the resonances, n, of an open flue pipe are nearly, but not quite in harmonic relationship, and shown that the acoustic output should contain components at frequencies which are close to n_i , he affirms that in the steady-state the frequencies Ω_i are locked into strict harmonic relationship so that $\Omega_i = i\Omega_1$ and justifies this citing the steady shape of pipe waveforms.[2] Later he states, " It is possible to envisage a condition in which this locking does not occur but several modes are exited seperately because of appropriate phase relations along the jet. The individual amplitudes a_i will then vary at relatively low frequencies. $\Omega_i \pm n\Omega_j \pm m\Omega_k$ such that $i \pm nj \pm mk = 0$. The raucous noise so produced is familiar to pipe voicers ...... "[3]

It seems likely therefore, that the effect of voicing is essentially two fold effecting the speed at which the pipe resonances lock into harmonic relationship and the overall steady tone of the pipes. It is significant that in our experiments the voicer produced similarity in the steady spectra of the pipes, although their onsets displayed characteristic differences. It becomes apparent therefore, that an organ pipe possesses, due to its physical shape and the material from which it is made, a uniqueness from which its tone quality is not divorced. It is not possible then that pipes made in materials which produce very different tonal effects could be voiced to sound similar. Voicing, it appears, without detracting from the skills involved, is a process by which a pipes' potential tone quality is achieved and subtly balanced with the tone of other pipes in the rank in order to produce an instrument with homogeneous tone quality.

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[1] Fletcher (41)

[2] cf p 930

[3] cf p 932

4.4 Wall Thickness / Wall Material Relationships: Theoretical

4.4.1 Introduction

The relationships between wall thickness and wall material are considered in two parts. First, theoretical links are examined, and subsequently, in the next section, experimental work is described. In this section a theoretical relationship linking wall thickness, resonator material, pipe geometry and the sound level radiated from the pipes is presented. It is used to compare calculated radiation levels to established scaling rules in order to find appropriate wall material thickness for pipes made in alternative materials.

4.4.2 Theory

In their study of organ pipe wall vibrations, Backus and Hundley[1] establish that the fractional distortion of pipe walls by vibration due to the motion of the internal standing wave on the wall, causes a frequency shift in the standing wave and that the sound power radiated through the yielding walls is directly related to this change in frequency, thus:[1]

$$\Delta f/f = -\tfrac{1}{2}\beta\rho_0 c^2 \qquad (1.)$$

where, Δf is the fractional change from frequency f.

β is the yield parameter of the tube.

ρ_0 is the air density.

c is the speed of sound in air.

In terms of the relative sound levels L_s and L_e produced by the walls and end, they conclude that :

$$L_s - L_e = 20 \log_{10} (2\ \Delta f/f) \qquad (2.)$$

The yield parameter involves wall thickness and the elasticity of the wall material as well as the pipes' diameter thus:

$$\beta = 3\ a^4\ c^5 / 4\ at^3 \qquad (3.)$$

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[1] Backus and Hundley (9)

where, $e = (1-b^2 / a^2)^{1/2}$ (4.)

a and b are semiaxis ($a \geq b$)

E is the modulus of Elasticity

t is the wall thickness

Combining equations 1 and 2 the general equation is:

$$L_s - L_e = 20 \log_{10} \left[2(K a^3 / Et^3) \right]$$

where, $K = 5.67 \times 10^5$

Backus and Hundley use this relationship to show that the frequency shift produced by tubes whether their walls are rigid or flexible, produces a change in radiation level through the walls which is insufficiently large compared with the radiation through the open end to effect the tone of certain pipes. They use this to conclude that the tonal structure of a pipe is determined only by its geometry.

4.4.3 Discussion

The relationship established between frequency effects, yielding pipe walls and the sound pressure radiated from pipes, provides a method of relating wall material properties and wall thickness in organ pipes. Backus and Hundley's calculations are made for two copper pipes, one square and the other round, sounding f-sharp 379 Hz. Considering the round pipe, it was fabricated in 10 mil sheet and had a diameter of 1½ inches, comparing this with the pipe scales normally adopted by organ builders, the figure for the wall thickness appears very thin compared with a similar pipe made in 70 per cent tin and the diameter represents a quite small scaled diapason or flute. This pipe is not therefore truly representative of a typical organ pipe.

It is reasonable therefore, to extend this theory to a wider range of pipe lengths and to calculate the sound radiation levels produced to find if the levels emitted through the walls are sufficiently large to effect the tone heard by listeners. Calculations are based firstly on the elastic modulus for 30 per cent Tin pipe metal, and secondly for 70 per cent pipe metal, the materials which were found in experiment 4.2.4 to produce such different tones. This enables the sound levels to be compared between the two types of pipe metal. Also, for comparison with these, the calculations are applied to steel and copper in order that the possible effects of other materials, if pipes were fabricated using the same thickness sheet, can be guaged against the more usual ones.

Table 4.5 shows calculated sound levels for 96 pipes beginning at C, 8 ft., and extending upwards seven octaves. The numeration of the pipes corresponds to that used in the pipe scales. The columns to the right of the pipe numbers indicate the levels ($L_s - L_e$) calculated for 30 per cent tin pipe metal and 70 per cent tin [illegible] based on the pipe scales mentioned. The scale indicates the diameter of each pipe and the wall thickness for each grade of metal at various wind pressures. All calculations have been based on the wall thickness scales for 2½ inches Wg wind. The 4th column, CU30, and the 6th column, ST30, indicate the radiation levels for copper and steel respectively, based on the scale for 30 per cent tin pipe metal. Similarly, columns 5 and 7 show values based on 70 per cent pipe metal scales. It will be noted the radiation levels in each column are not a gradually decreasing list but are apparently erratic. This is due to the specification of wall thickness in increments of 3, 4, 5 or 6 pipes depending on the position in the rank, whereas diameters are specified separately for each pipe.

Comparison of the values calculated using Backus and Hundley's formula for pipe metal shows an unmistakeable similarity. Dissimilarities are largest at the low end of the table where typical divergencies are 5 per cent though some reach almost 8 per cent. At the upper end of the table 3.5 per cent is the maximum divergence encountered. The levels calculated for copper and steel show that copper with wall thickness similar to 30 per cent pipe metal should radiate 12 dB less sound than the pipe metal and steel 20 dB less. For the 70 per cent pipe metal wall thickness, the levels were closer, copper radiating 8 dB less and steel 15 dB less.

The levels indicated are the sound power radiated by the yielding walls below the level of sound from the pipes' open end. First, in consideration of the implications of the results, the audibility of these sounds must be discussed. Our awareness of the sound radiated from the pipe walls is dependent upon the frequency of the sound and its amplitude relative to the sound radiated from the open end. Although the overall SPL is an influencing factor,[1] amidst

[1] Littler (68) 131

TABLE 4.5 Comparison of Radiation Levels

$(L_s - L_e)$

PIPE	30PC	70PC	CU30	CU70	ST 30	ST 70
32	-8.275	-8.826	-20.957	-17.073	-28.133	-24.250
33	-9.403	-9.954	-22.085	-18.201	-29.261	-25.378
34	-10.533	-11.083	-23.214	-19.331	-30.391	-26.507
35	-9.578	-10.283	-22.259	-18.530	-29.435	-25.707
36	-10.703	-11.409	-23.385	-19.656	-30.561	-26.832
37	-11.832	-12.537	-24.513	-20.784	-31.690	-27.961
38	-10.215	-11.580	-22.897	-19.828	-30.073	-27.004
39	-11.345	-12.710	-24.027	-20.958	-31.203	-28.134
40	-12.476	-13.841	-25.158	-22.089	-32.334	-29.265
41	-11.596	-12.699	-24.278	-20.947	-31.454	-28.123
42	-12.728	-13.831	-25.410	-22.079	-32.586	-29.255
43	-13.854	-14.957	-26.536	-23.205	-33.712	-30.381
44	-12.816	-13.608	-25.497	-21.855	-32.674	-29.032
45	-13.940	-14.732	-26.621	-22.979	-33.797	-30.156
46	-15.071	-15.863	-27.752	-24.110	-34.929	-31.287
47	-13.831	-14.248	-26.513	-22.496	-33.689	-29.672
48	-14.952	-15.370	-27.634	-23.617	-34.810	-30.793
49	-16.082	-16.499	-28.763	-24.747	-35.940	-31.923
50	-14.607	-14.563	-27.288	-22.810	-34.465	-29.987
51	-15.734	-15.690	-28.415	-23.937	-35.591	-31.113
52	-16.871	-16.827	-29.553	-25.075	-36.729	-32.251
53	-15.091	-14.466	-27.773	-22.713	-34.949	-29.890
54	-16.224	-15.599	-28.906	-23.847	-36.082	-31.023
55	-17.359	-16.734	-30.041	-24.981	-37.217	-32.158
56	-15.222	-15.927	-27.904	-24.175	-35.080	-31.351
57	-16.347	-17.052	-29.029	-25.300	-36.205	-32.476
58	-17.471	-18.176	-30.153	-26.424	-37.329	-33.600
59	-18.602	-19.307	-31.284	-27.555	-38.460	-34.731
60	-17.936	-18.353	-30.617	-26.601	-37.794	-33.777
61	-19.065	-19.483	-31.747	-27.730	-38.923	-34.906
62	-20.190	-20.608	-32.872	-28.855	-40.048	-36.031
63	-21.334	-21.751	-34.015	-29.999	-41.192	-37.175
64	-20.518	-20.599	-33.199	-28.846	-40.375	-36.022
65	-21.654	-21.735	-34.336	-29.983	-41.512	-37.159
66	-22.791	-22.872	-35.473	-31.120	-42.649	-38.296
67	-23.918	-23.999	-36.600	-32.247	-43.776	-39.423
68	-22.946	-22.630	-35.628	-30.877	-42.804	-38.053
69	-23.261	-22.944	-35.943	-31.192	-43.119	-38.368
70	-25.223	-24.907	-37.905	-33.154	-45.081	-40.330
71	-26.331	-26.014	-39.013	-34.262	-46.189	-41.438
72	-27.469	-27.152	-40.151	-35.400	-47.327	-42.576
73	-28.609	-28.292	-41.291	-36.540	-48.467	-43.716
74	-27.461	-26.666	-40.143	-34.914	-47.319	-42.090
75	-28.588	-27.793	-41.269	-36.040	-48.445	-43.216
76	-29.719	-28.924	-42.401	-37.172	-49.577	-44.348
77	-30.843	-30.048	-43.525	-38.296	-50.701	-45.472
78	-31.968	-31.173	-44.650	-39.421	-51.826	-46.597
79	-33.092	-32.297	-45.774	-40.545	-52.950	-47.721
80	-31.743	-30.362	-44.424	-38.610	-51.601	-45.786
81	-32.872	-31.492	-45.554	-39.739	-52.730	-46.916
82	-34.009	-32.528	-46.690	-40.876	-53.867	-48.052
83	-35.136	-33.755	-47.817	-42.003	-54.994	-49.179
84	-36.265	-34.885	-48.947	-43.132	-56.123	-50.309
85	-37.396	-36.016	-50.078	-44.263	-57.254	-51.439
86	-37.189	-35.463	-49.670	-43.711	-57.047	-50.887
87	-38.315	-36.589	-50.996	-44.836	-58.172	-52.013
88	-39.434	-37.708	-52.116	-45.956	-59.292	-53.132
89	-40.564	-38.838	-53.245	-47.086	-60.422	-54.262

90	-41.703	-39.977	-54.385	-48.225	-61.561	-55.401
91	-42.829	-41.104	-55.511	-49.351	-62.687	-56.527
92	-41.063	-40.437	-53.744	-48.685	-60.920	-55.861
93	-42.198	-41.573	-54.880	-49.821	-62.056	-56.997
94	-43.311	-42.686	-55.993	-50.934	-63.169	-58.110
95	-44.448	-43.823	-57.130	-52.071	-64.306	-59.247
96	-45.583	-44.958	-58.265	-53.205	-65.441	-60.382
97	-46.713	-46.088	-59.395	-54.336	-66.571	-61.512
98	-44.574	-45.280	-57.256	-53.527	-64.432	-60.703
99	-45.686	-46.391	-58.367	-54.639	-65.544	-61.815
100	-46.815	-47.520	-59.496	-55.768	-66.673	-62.944
101	-47.962	-48.667	-60.643	-56.914	-67.819	-64.091
102	-49.091	-49.796	-61.773	-58.044	-68.949	-65.220
103	-48.437	-50.940	-61.119	-59.188	-68.295	-66.364
104	-49.557	-49.975	-62.239	-58.222	-69.415	-65.398
105	-50.688	-51.105	-63.369	-59.353	-70.546	-66.529
106	-51.786	-52.204	-64.468	-60.451	-71.644	-67.628
107	-52.933	-53.351	-65.615	-61.598	-72.791	-68.775
108	-54.042	-54.460	-66.724	-62.707	-73.900	-69.883
109	-53.270	-55.618	-65.951	-63.866	-73.128	-71.042
110	-54.383	-54.464	-67.064	-62.711	-74.241	-69.888
111	-54.532	-54.613	-67.213	-62.860	-74.389	-70.036
112	-56.655	-56.736	-69.336	-64.983	-76.512	-72.159
113	-57.757	-57.838	-70.438	-66.085	-77.614	-73.261
114	-58.907	-58.988	-71.589	-67.236	-78.765	-74.412
115	-57.964	-60.131	-70.645	-68.378	-77.822	-75.554
116	-59.094	-61.261	-71.776	-69.508	-78.952	-76.685
117	-60.343	-62.510	-73.025	-70.757	-80.201	-77.934
118	-61.303	-63.470	-73.985	-71.717	-81.161	-78.894
119	-62.446	-64.612	-75.127	-72.860	-82.303	-80.036
120	-63.564	-65.731	-76.246	-73.978	-83.422	-81.155
121	-62.466	-64.416	-75.147	-72.664	-82.323	-79.840
122	-63.606	-65.556	-76.287	-73.804	-83.464	-80.980
123	-64.711	-66.662	-77.393	-74.909	-84.569	-82.085
124	-65.865	-67.816	-78.547	-76.064	-85.723	-83.240
125	-66.978	-68.929	-79.660	-77.176	-86.836	-84.353
126	-68.141	-70.092	-80.823	-78.339	-87.999	-85.515
127	-66.771	-71.265	-79.452	-79.452	-86.629	-86.629

a higher overall level, the amplitude of a tone in tune with another will be identified at a lower level, the extent of the difference, at the frequencies above which the radiation levels shown on the graohs are imperceivable, is too slight to be relevant. The minimum level which will be heard amidst an 80 dB overall level is approximately - 30 dB at 880 Hz.[1] Thus the radiation levels for pipes above number 77 in both the pipe metal calculations, are too small to influence our perception of the pipes' timbre. Our concern is therefore, with pipes larger than number 77, longer than 175 mm in resonator length. Smaller than this the pipe wall material should have no noticeable effect on the sound radiated.

The striking similarity between the radiated levels among the pipe metal resonators constructed according to traditional scaling rules is curious, especially since the levels produced by the same rules in other materials are so much more divergent, but the implications of this finding are not clear. Regarding the influence of wall material on tone quality, the steady state analysis in section 4.1 demonstrates the similarity of steady tone between steel and pipe metal resonators. From the present calculations, changes in SPL of -15 or -20 dB would be anticipated between the wall's sound radiation levels in pipe metal and steel pipes. This has apparently produced no noticeable effect.

There is no detailed experimental data about wall thickness and material effects on the onset of pipe speech and it is not possible therefore to compare the calculation with other experimentally derived data. Before proceeding with experimental work about this, the validity of the approach was tested by using the sound levels calculated to suggest suitable wall thickness for pipes made in other materials. The thickness identified was that which would produce the correct sound radiation level. Two tables were produced, one based on the 30 per cent pipe metal levels and the other on the 70 per cent levels. Calculations were made for copper, zinc and 45 per cent tin pipe metal, which are materials also used by organ builders and which could be checked against the wall thickness scales normally used for these metals. Also calculated were levels for aluminium and steel. The 30 per cent table (Table 4.6) shows, in addition, the usual wall thickness for 30 per cent pipe metal and, under the column PM70, gives the re-calculated value based on 30 per cent tin pipe metal levels for 70 per cent pipe metal. The reverse is true in the table based on 70 per cent tin values. (Table 4.7)

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[1] Littler (68) p 127

TABLE 4.6

WALL THICKNESS TO PRODUCE 30 PC LEVELS

PIPE	AL	CU	ZK	ST	PM30	PM45	PM70
32	1.25	1.01	1.09	0.77	1.65	1.58	1.39
33	1.25	1.01	1.09	0.77	1.65	1.58	1.39
34	1.25	1.01	1.09	0.77	1.65	1.58	1.39
35	1.15	0.94	1.01	0.71	1.52	1.46	1.29
36	1.15	0.94	1.01	0.71	1.52	1.46	1.29
37	1.15	0.94	1.01	0.71	1.52	1.46	1.29
38	1.04	0.84	0.91	0.64	1.37	1.31	1.16
39	1.04	0.84	0.91	0.64	1.37	1.31	1.16
40	1.04	0.84	0.91	0.64	1.37	1.31	1.16
41	0.96	0.78	0.84	0.59	1.27	1.21	1.07
42	0.96	0.78	0.84	0.59	1.27	1.21	1.07
43	0.96	0.78	0.84	0.59	1.27	1.21	1.07
44	0.88	0.72	0.77	0.55	1.17	1.12	0.99
45	0.88	0.72	0.77	0.55	1.17	1.12	0.99
46	0.88	0.72	0.77	0.55	1.17	1.12	0.99
47	0.81	0.66	0.71	0.50	1.07	1.02	0.90
48	0.81	0.66	0.71	0.50	1.07	1.02	0.90
49	0.81	0.66	0.71	0.50	1.07	1.02	0.90
50	0.73	0.59	0.64	0.45	0.97	0.92	0.81
51	0.73	0.59	0.64	0.45	0.97	0.92	0.81
52	0.73	0.59	0.64	0.45	0.97	0.92	0.81
53	0.65	0.53	0.57	0.40	0.86	0.83	0.73
54	0.65	0.53	0.57	0.40	0.86	0.83	0.73
55	0.65	0.53	0.57	0.40	0.86	0.83	0.73
56	0.58	0.47	0.50	0.36	0.76	0.73	0.64
57	0.58	0.47	0.50	0.36	0.76	0.73	0.64
58	0.58	0.47	0.50	0.36	0.76	0.73	0.64
59	0.58	0.47	0.50	0.36	0.76	0.73	0.64
60	0.54	0.44	0.47	0.33	0.71	0.68	0.60
61	0.54	0.44	0.47	0.33	0.71	0.68	0.60
62	0.54	0.44	0.47	0.33	0.71	0.68	0.60
63	0.54	0.44	0.47	0.33	0.71	0.68	0.60
64	0.50	0.41	0.44	0.31	0.66	0.63	0.56
65	0.50	0.41	0.44	0.31	0.66	0.63	0.56
66	0.50	0.41	0.44	0.31	0.66	0.63	0.56
67	0.50	0.41	0.44	0.31	0.66	0.63	0.56
68	0.46	0.37	0.40	0.28	0.61	0.58	0.51
69	0.46	0.37	0.40	0.28	0.61	0.58	0.51
70	0.46	0.37	0.40	0.28	0.61	0.58	0.51
71	0.46	0.37	0.40	0.28	0.61	0.58	0.51
72	0.46	0.37	0.40	0.28	0.61	0.58	0.51
73	0.46	0.37	0.40	0.28	0.61	0.58	0.51
74	0.42	0.34	0.37	0.26	0.56	0.53	0.47
75	0.42	0.34	0.37	0.26	0.56	0.53	0.47
76	0.42	0.34	0.37	0.26	0.56	0.53	0.47
77	0.42	0.34	0.37	0.26	0.56	0.53	0.47
78	0.42	0.34	0.37	0.26	0.56	0.53	0.47
79	0.42	0.34	0.37	0.26	0.56	0.53	0.47
80	0.38	0.31	0.34	0.24	0.51	0.49	0.43
81	0.38	0.31	0.34	0.24	0.51	0.49	0.43
82	0.38	0.31	0.34	0.24	0.51	0.49	0.43
83	0.38	0.31	0.34	0.24	0.51	0.49	0.43
84	0.38	0.31	0.34	0.24	0.51	0.49	0.43
85	0.38	0.31	0.34	0.24	0.51	0.49	0.43
86	0.36	0.30	0.32	0.23	0.48	0.46	0.41
87	0.36	0.30	0.32	0.23	0.48	0.46	0.41
88	0.36	0.30	0.32	0.23	0.48	0.46	0.41
89	0.36	0.30	0.32	0.23	0.48	0.46	0.41
90	0.36	0.30	0.32	0.23	0.48	0.46	0.41
91	0.36	0.30	0.32	0.23	0.48	0.46	0.41
92	0.33	0.27	0.29	0.20	0.43	0.41	0.36

93	0.33	0.27	0.29	0.20	0.43	0.41	0.36
94	0.33	0.27	0.29	0.20	0.43	0.41	0.36
95	0.33	0.27	0.29	0.20	0.43	0.41	0.36
96	0.33	0.27	0.29	0.20	0.43	0.41	0.36
97	0.33	0.27	0.29	0.20	0.43	0.41	0.36
98	0.29	0.23	0.25	0.18	0.38	0.36	0.32
99	0.29	0.23	0.25	0.18	0.38	0.36	0.32
100	0.29	0.23	0.25	0.18	0.38	0.36	0.32
101	0.29	0.23	0.25	0.18	0.38	0.36	0.32
102	0.29	0.23	0.25	0.18	0.38	0.36	0.32
103	0.27	0.22	0.24	0.17	0.36	0.34	0.30
104	0.27	0.22	0.24	0.17	0.36	0.34	0.30
105	0.27	0.22	0.24	0.17	0.36	0.34	0.30
106	0.27	0.22	0.24	0.17	0.36	0.34	0.30
107	0.27	0.22	0.24	0.17	0.36	0.34	0.30
108	0.27	0.22	0.24	0.17	0.36	0.34	0.30
109	0.25	0.20	0.22	0.15	0.33	0.32	0.28
110	0.25	0.20	0.22	0.15	0.33	0.32	0.28
111	0.25	0.20	0.22	0.15	0.33	0.32	0.28
112	0.25	0.20	0.22	0.15	0.33	0.32	0.28
113	0.25	0.20	0.22	0.15	0.33	0.32	0.28
114	0.25	0.20	0.22	0.15	0.33	0.32	0.28
115	0.23	0.19	0.20	0.14	0.30	0.29	0.26
116	0.23	0.19	0.20	0.14	0.30	0.29	0.26
117	0.23	0.19	0.20	0.14	0.30	0.29	0.26
118	0.23	0.19	0.20	0.14	0.30	0.29	0.26
119	0.23	0.19	0.20	0.14	0.30	0.29	0.26
120	0.23	0.19	0.20	0.14	0.30	0.29	0.26
121	0.21	0.17	0.18	0.13	0.28	0.27	0.24
122	0.21	0.17	0.18	0.13	0.28	0.27	0.24
123	0.21	0.17	0.18	0.13	0.28	0.27	0.24
124	0.21	0.17	0.18	0.13	0.28	0.27	0.24
125	0.21	0.17	0.18	0.13	0.28	0.27	0.24
126	0.21	0.17	0.18	0.13	0.28	0.27	0.24
127	0.19	0.16	0.17	0.12	0.25	0.24	0.21

WALL THICKNESS TO PRODUCE 70 PC LEVELS TABLE 4.7

PIPE	AL	CU	ZK	ST	PM30	PM45	PM70
32	1.27	1.04	1.11	0.79	1.69	1.61	1.42
33	1.27	1.04	1.11	0.79	1.69	1.61	1.42
34	1.27	1.04	1.11	0.79	1.69	1.61	1.42
35	1.18	0.96	1.04	0.73	1.57	1.50	1.32
36	1.18	0.96	1.04	0.73	1.57	1.50	1.32
37	1.18	0.96	1.04	0.73	1.57	1.50	1.32
38	1.09	0.89	0.96	0.67	1.45	1.38	1.22
39	1.09	0.89	0.96	0.67	1.45	1.38	1.22
40	1.09	0.89	0.95	0.67	1.45	1.38	1.22
41	1.00	0.81	0.88	0.62	1.32	1.27	1.12
42	1.00	0.81	0.88	0.62	1.32	1.27	1.12
43	1.00	0.81	0.88	0.62	1.32	1.27	1.12
44	0.91	0.74	0.80	0.56	1.20	1.15	1.02
45	0.91	0.74	0.80	0.56	1.20	1.15	1.02
46	0.91	0.74	0.80	0.56	1.20	1.15	1.02
47	0.82	0.67	0.72	0.51	1.08	1.04	0.91
48	0.82	0.67	0.72	0.51	1.08	1.04	0.91
49	0.82	0.67	0.72	0.51	1.08	1.04	0.91
50	0.73	0.59	0.64	0.45	0.96	0.92	0.81
51	0.73	0.59	0.64	0.45	0.96	0.92	0.81
52	0.73	0.59	0.64	0.45	0.96	0.92	0.81
53	0.64	0.52	0.56	0.39	0.84	0.81	0.71
54	0.64	0.52	0.56	0.39	0.84	0.81	0.71
55	0.64	0.52	0.56	0.39	0.84	0.81	0.71
56	0.59	0.48	0.52	0.37	0.78	0.75	0.66

57	0.59	0.48	0.52	0.37	0.78	0.75	0.66
58	0.59	0.48	0.52	0.37	0.78	0.75	0.66
59	0.59	0.48	0.52	0.37	0.78	0.75	0.66
60	0.55	0.44	0.48	0.34	0.72	0.69	0.61
61	0.55	0.44	0.48	0.34	0.72	0.69	0.61
62	0.55	0.44	0.48	0.34	0.72	0.69	0.61
63	0.55	0.44	0.48	0.34	0.72	0.69	0.61
64	0.50	0.41	0.44	0.31	0.66	0.63	0.56
65	0.50	0.41	0.44	0.31	0.66	0.63	0.56
66	0.50	0.41	0.44	0.31	0.66	0.63	0.56
67	0.50	0.41	0.44	0.31	0.66	0.63	0.56
68	0.46	0.37	0.40	0.28	0.60	0.58	0.51
69	0.46	0.37	0.40	0.28	0.60	0.58	0.51
70	0.46	0.37	0.40	0.28	0.60	0.58	0.51
71	0.46	0.37	0.40	0.28	0.60	0.58	0.51
72	0.46	0.37	0.40	0.28	0.60	0.58	0.51
73	0.46	0.37	0.40	0.28	0.60	0.58	0.51
74	0.41	0.33	0.36	0.25	0.54	0.52	0.46
75	0.41	0.33	0.36	0.25	0.54	0.52	0.46
76	0.41	0.33	0.36	0.25	0.54	0.52	0.46
77	0.41	0.33	0.36	0.25	0.54	0.52	0.46
78	0.41	0.33	0.36	0.25	0.54	0.52	0.46
79	0.41	0.33	0.36	0.25	0.54	0.52	0.46
80	0.36	0.30	0.32	0.22	0.48	0.46	0.41
81	0.36	0.30	0.32	0.22	0.48	0.46	0.41
82	0.36	0.30	0.32	0.22	0.48	0.46	0.41
83	0.36	0.30	0.32	0.22	0.48	0.46	0.41
84	0.36	0.30	0.32	0.22	0.48	0.46	0.41
85	0.36	0.30	0.32	0.22	0.48	0.46	0.41
86	0.34	0.26	0.30	0.21	0.45	0.43	0.38
87	0.34	0.28	0.30	0.21	0.45	0.43	0.38
88	0.34	0.28	0.30	0.21	0.45	0.43	0.38
89	0.34	0.28	0.30	0.21	0.45	0.43	0.38
90	0.34	0.28	0.30	0.21	0.45	0.43	0.38
91	0.34	0.28	0.30	0.21	0.45	0.43	0.38
92	0.32	0.26	0.28	0.20	0.42	0.40	0.36
93	0.32	0.26	0.28	0.20	0.42	0.40	0.36
94	0.32	0.26	0.28	0.20	0.42	0.40	0.36
95	0.32	0.26	0.28	0.20	0.42	0.40	0.36
96	0.32	0.26	0.28	0.20	0.42	0.40	0.36
97	0.32	0.26	0.28	0.20	0.42	0.40	0.36
98	0.30	0.24	0.26	0.18	0.39	0.37	0.33
99	0.30	0.24	0.26	0.18	0.39	0.37	0.33
100	0.30	0.24	0.26	0.18	0.39	0.37	0.33
101	0.30	0.24	0.26	0.18	0.39	0.37	0.33
102	0.30	0.24	0.26	0.18	0.39	0.37	0.33
103	0.30	0.24	0.26	0.18	0.39	0.37	0.33
104	0.27	0.22	0.24	0.17	0.36	0.35	0.30
105	0.27	0.22	0.24	0.17	0.36	0.35	0.30
106	0.27	0.22	0.24	0.17	0.36	0.35	0.30
107	0.27	0.22	0.24	0.17	0.36	0.35	0.30
108	0.27	0.22	0.24	0.17	0.36	0.35	0.30
109	0.27	0.22	0.24	0.17	0.36	0.35	0.30
110	0.25	0.20	0.22	0.15	0.33	0.32	0.28
111	0.25	0.20	0.22	0.15	0.33	0.32	0.28
112	0.25	0.20	0.22	0.15	0.33	0.32	0.28
113	0.25	0.20	0.22	0.15	0.33	0.32	0.28
114	0.25	0.20	0.22	0.15	0.33	0.32	0.28
115	0.25	0.20	0.22	0.15	0.33	0.32	0.28
116	0.25	0.20	0.22	0.15	0.33	0.32	0.28
117	0.25	0.20	0.22	0.15	0.33	0.32	0.28

118	0.25	0.20	0.22	0.15	0.33	0.32	0.28
119	0.25	0.20	0.22	0.15	0.33	0.32	0.28
120	0.25	0.20	0.22	0.15	0.33	0.32	0.28
121	0.23	0.19	0.20	0.14	0.30	0.29	0.25
122	0.23	0.19	0.20	0.14	0.30	0.29	0.25
123	0.23	0.19	0.20	0.14	0.30	0.29	0.25
124	0.23	0.19	0.20	0.14	0.30	0.29	0.25
125	0.23	0.19	0.20	0.14	0.30	0.29	0.25
126	0.23	0.19	0.20	0.14	0.30	0.29	0.25
127	0.23	0.19	0.20	0.14	0.30	0.29	0.25

Comparing the wall thickness calculated for zinc, copper and 45 per cent tin pipe metal with the scales used in practice for these materials, they show good correlation though the calculated values are in all cases, slightly larger than the standard thickness.

4.4.4 Summary

The application of Backus and Hundley's theory to the calculation of wall thickness for pipes in other materials, has been fairly successful. Known values were re-calculated quite well and inaccuracies tended to suggest marginally too thick resonator walls.

4.5 Wall Thickness / Wall Material Relationships: Experimental

4.5.1 Introduction

In this section, the second concerning wall thickness and materials, experimental work done to investigate the effect on tone of wall material and wall thickness is considered. Two experiments were undertaken. A comparison between the tonal effects produced by resonators fabricated in similar alloys of pipe metal over a range of wall thickness and the effects of resonators of similar dimensions but fabricated in other materials is the subject of the second experiment. The first is an attempt to validate the conclusions of the theoretical work described in the previous section (4.4)

4.5.2 Practical Investigation of the Theory Relating Pipe Wall Material and Wall Thickness

4.5.2.1 Method

To demonstrate the validity of the theory discussed in section 4.4, the wall thickness for aluminium which had been calculated would yield the tone quality associated with 70 per cent tin pipe metal was adopted in the construction of two pipes. In each the foot and resonator were aluminium, the languid, as is common practice, was 15 per cent tin pipe metal and the lips 70 per cent tin pipe metal. Since a comparison with other pipes is of limited value due to the factors discussed in Chapter 2, and the tone quality wanted, that with the characteristic onset chiff, has been defined, the pipes were voiced by an organ builder and his opinions of their tonal worth sought. His opinions may be compared with the more controlled experiment using pipe C in section 4.5.3 where 70 per cent tin and aluminium resonators with calculated similar sound radiation qualities, are compared.

The two pipes are as follows:-

Frequency	Scale No.	Material	Rad. cm.	Wall th. cm
380 Hz	77	Aluminium	1.101	0.41
220 Hz	53	Aluminium	3.113	0.64

Pipe 77 was chosen because it is at the junction where it is supposed that materials effects on tone will not be detected by human hearing. The other pipe, number 53, is in the area of good auditory perception; the region, according to later results (cf. section 4.5.3.3 and section 5), where materials influence on tone quality is greatest.

4.5.2.2 Result

The aural impression given by both of the pipes after they had been voiced was similar to that which would be expected from a high percentage tin pipe: a hollow, chiff-like onset. This demonstrates that alternative materials can be used satisfactorily at least for certain pipes. The question of the relative influence of wall material and wall thickness to lip material which is raised by this is discussed later (section 5.2.5), as in the next experiment the effect of resonator material on onset tone is investigated independently of lip materials.

4.5.3 Effects of Combined Wall Material and Wall Thickness Changes

4.5.3.1 Method

The technique discussed previously and used in the experiment in section 4.1 of removing the resonator from the pipe foot and using this as a common driver for various resonators which are mounted upon it using a rubber collar, is applied to this experiment. Here however, the analysis involves both steady state and onset. The latter is discussed fully in section 3.1.3 and further in appendix B, where also will be found details of the analysis parameters adopted for each of the pipes considered here.

The experiment involves three pipes, A, B, and C. Pipe A, the highest pitched of the three, sounds F, 2901 Hz. Pipe B sounds A at 900 Hz and Pipe C F♯ 192 Hz. The pipes were chosen in view of the comments about perception of sounds in section 3.1.4. Pipe B represents the lower end of the range identified here, Pipe A is close to the highest frequency used in organ pipes and pipe C was chosen as an example near the lower end of the spectrum. All the pipes were fabricated in 30 per cent tin pipe metal alloy and had been voiced as diapasons without chiff onsets.

The choice of materials for comparison with pipe metal involved consideration of materials sometimes used in organ building, from which useful information might be glened, and also materials which might

TABLE 4.8

RESONATOR DETAIL

WALL THICKNESS AND MATERIAL RELATIONSHIPS : EXPERIMENTAL

4.8a PIPE A

Ref.	Freq. (Hz)	Scale No.	Material	Cut Off Resonator Length	Radius (cm)	Wall Th (cm)	Ls - Le dB
A 1-1	2900	108	Pipe Metal 70		0.385	0.02	-35.871
A 1-2	"	"	"	"	"	0.04	-53.933
A 1-3	"	"	"	"	"	0.091	-75.352
A 2-1	"	"	Copper	"	"	0.02	-44.119
A 2-2	"	"	"	"	"	0.04	-62.181
A 2-3	"	"	"	"	"	0.091	-83.599
A 3-1	"	"	Paper	"	"	0.02	-21.840
A 3-2	"	"	"	"	"	0.04	-39.902
A 3-3	"	"	"	"	"	0.091	-61.321

4.8b PIPE B

B 1-1	900	77	Pipe Metal 30		0.79	0.03	-28.273
B 1-2	"	"	"	"	"	0.056	-39.537
B 1-3	"	"	"	"	"	0.163	-67.377
B 2-1	"	"	Copper	"	"	0.03	-35.954
B 2-2	"	"	"	"	"	0.056	-52.218
B 2-3	"	"	"	"	"	0.163	-80.058
B 3-1	"	"	Paper	"	"	0.03	-13.675
B 3-2	"	"	"	"	"	0.056	-29.939
B 3-3	"	"	"	"	"	0.163	-57.779
B 4-1	"	"	Steel	"	"	0.163	-87.234

4.8c <u>PIPE C</u>

Ref.	Freq. (Hz)	Scale No.	Material	Cut Off Resonator Length	Radius (cm)	Wall Th (cm)	Ls - Le dB
C 1-1	194	50	Pipe Metal 70		2.85	0.07	-16.352
C 1-2	"	"	"	"	"	0.12	-30.397
C 1-3	"	"	Pipe Metal 30	"	"	0.98	-21.212
C 1-4	"	"	"	"	"	0.105	-22.484
C 2-1	"	"	Copper	"	"	0.163	-46.625
C 2-2	"	"	"	"	"	0.1016	-35.165
C 3-1	"	"	Aluminium	"	"	0.061	-15.637

satisfy the mallibility criterion for an alternative to pipe metal. For pipes A and B, pipe metal is compared with copper and paper resonators and also one made from steel. Pipe C too had copper resonators but, due to fabrication problems, paper was not included. An aluminium resonator was investigated together also with resonators in 70 per cent and 30 per cent metal.

The choice of wall thickness for each of the resonator materials was made with reference to the thickness of the original pipe metal resonator associated with each pipe and the calculated sound radiation levels anticipated in the work of section 4.3. Each resonator was to be made in three thicknesses, one corresponding to the original resonator thickness, the other thinner and one thicker than this. The detail of the pipes is shown in Table 4.8.

In pipe A the original pipe metal resonator's wall thickness measured 0.04 cm and, since the radiation levels are not a primary consideration for pipes of this frequency, one thickness chosen was the thinnest workable 30 per cent tin sheet, found to be 0.02 cm. The other wall thickness chosen, which was intended to be thicker than the original, was 0.091 cm, a convenient sheet metal standard (20 swg) in which copper is available. The pipe resonators A 1-1 and A 1-3 were produced by planing and scraping some thicker pipe metal. The sheet for the copper resonators A 2-1 and A 2-2 was rolled and, together with the 20 swg sheet used in A 2-3, was annealed before fabrication. The seams of both pipe metal and copper resonators, with the exception of A 2-3 which was silver-soldered, were soft soldered using 60-40 per cent lead-tin solder.

Pipe B's resonator thickness was 0.056 cm, the thickness of 20 swg sheet. 0.03 cm was chosen for the thinner wall thickness primarily because it was reasonably the thinnest sheet of its size which could be worked, but also because it was calculated to yield -23 dB sound level which is similar to that calculated for resonator B 3-2 and is close to the minimum level of auditory discrimination anticipated. Again, for the thicker wall thickness a measurement much thicker than the original was selected from the range of standard gauges. 16 swg was chosen, which is almost 3 times the thickness of resonator B 1-2. As well as copper sheet being available at this spectification, a cold drawn steel tube of the correct diameter was procured commercially.

Materials availability effected the selection of wall thickness for pipe C. The copper version of the original resonator, made from 0.105 cm 30 per cent tin pipe metal sheet, was fabricated from 19 swg sheet which has a thickness of 0.1016 cm. A comparison of the original resonator with one in 70 per cent pipe metal was desired, and a sheet 0.12 cm thick metal provided this. Unfortunately, the size and high tin content of the sheet prohibited it being manually scraped to a closer tolerance. Two other pipe metal sheets were also considered, a 30 per cent tin one of virtually the same thickness as the original and a 0.07 cm sheet of 70 per cent tin metal. The aluminium resonator's thickness was chosen that it should produce the same radiation level as the 70 per cent, 0.07 cm resonator. One resonator, made in 16 swg copper was the only one thicker than the original pipe metal one.

All the tubes were formed around BDMS mandrils turned to the internal diameters of the pipes. Attention was given to the closeness of fit to the mandril and also to the cylindricality of the tubes.

4.5.3.2 Results

The 26 graphs, figures 4.13 to 4.38, present the onset curves for each of the resonators tested. Figures 4.13 to 4.21 show the results from pipe A which are presented in groups of three; figures 4.13, 4.14 and 4.15 showing the results of pipe metal resonators, figures 4.16, 4.17 and 4.18 show those obtained from the copper resonators and the effect of paper resonators is shown in figures 4.19, 4.20 and 4.21. In general the onset of the fundamental is very similar in each instance, though close examination reveals a slightly faster initial rise in the paper resonator graphs (figure 4.19 to 4.21) than the thinner copper ones (figure 4.16 and 4.17). It appears that the fundamentals' onset in the thinner walled resonators is accomplished in two stages as is shown in figures 4.13, 4.16 and 4.19 and also, to a lesser extent, in 4.14, 4.17 and 4.20. A slight flat on the curve is followed by a secondary steep rise which occurs between 30 mS and 35 mS. The onsets of the other three harmonics are very similar too, though in figure 4.13, the 3rd and 4th harmonics are much more unsteady than the other harmonics.

The results of pipe B, figures 4.22 to 4.31 , are in four groups; figures 4.22, 4.23 and 4.24 are the pipe metal resonator onsets, figures 4.25, 4.26 and 4.27 are those from the copper resonators and figures 4.28, 4.29 and 4.30 present those from the paper resonators. Figure 4.31 shows the onset analysis graph of the steel resonator B4.1 which is similar in thickness to the resonators whose onset graphs are shown at the bottom of the previous three pages - figures 4.24, 4.27 and 4.30. Unlike the results of pipe A these onsets show marked dissimilarities including differences in the signals onsets. Figure 4.23 shows the onset of the pipe with a resonator similar in material and thickness to the pipes' original - B1.2 . In this instance the onset has reached its steady condition after 80 mS, the fundamental and second harmonic rising quickly at first with a slight delay before reaching their steady levels after 60 mS. Harmonics 3 and 4 take longer to settle, both of them rising slightly in the initial stages above their steady amplitude. In the thinner walled pipe metal resonator (figure 4.22) this phenomenon is more noticeable particularly in the early part of the 4th harmonics' onset. The behaviour of the other harmonics is similar to that described in figure 4.23.

In figure 4.24 the fundamental and second harmonic take longer to reach their maximum and the 4th harmonic is less stable than in either of the previous instances, though the final levels are reached within the same period as before. The 1.63 mm copper resonator, figure 4.27, the paper one (figure 4.30) and the steel resonator (figure 4.31) also reveal similarly unstable onsets. In the latter case the fundamental builds up more slowly than in the others where the fundamentals' initial behaviour is little effected. These onsets display in all harmonics and in all but the pipe metal one, the steady condition is reached only after 90 to 100 mS.

Figures 4.26 and 4.27 are broadly similar to the 0.56 mm pipe metal result, figure 4.23 . In both, the fundamentals' initial rise is faster but only slightly and the 3rd and 4th harmonics display similar instability for 60 mS to 70 mS. Other than the initial overshoot, the result of the 0.3 mm copper resonator is similar to that of the thicker copper resonator, figure 4.26. The thinnest paper one though, is markedly different, the onset of the fundamental and second harmonic being slightly slower than in the version in figure 4.29 and the lower harmonics remain very unstable until after 90 mS has elapsed.

Seven graphs comprise the results of pipe C. Figures 4.32 and 4.33 and figures 4.34 and 4.35 show results from 70 per cent and 30 per cent tin pipe metal resonators respectively. Figures 4.36 and 4.37 present those from two copper resonators and figure 4.38 the aluminium one. The onsets of the two sets of pipe metal resonators are very different but comparison of the two 30 per cent tin and the two 70 per cent tin resonators onsets shows that within each group similarity exists. The 70 per cent tin resonators onsets and those of the 30 per cent tin resonators have relatively similar instability in the 2nd and 3rd harmonics which become steady after 280 mS to 300 mS. The fundamentals of the former, however, are slow to build up. In figures 4.32 after 160 mS had elapsed only half the final amplitude is achieved and in figure 4.33 200 mS is taken before this is reached. The 70 per cent tin resonators onsets subsequently build up quite rapidly reaching their final amplitude by 240 mS and 290 mS respectively. In the case of the 30 per cent tin resonators the fundamental builds up steadily to almost its final level by about 170 mS in both figures 4.34 and 4.35.

The 1.63 mm thick copper resonators' onset, figure 4.36, is very similar to the 30 per cent tin pipe metal one in figure 4.35. The other copper one (figure 4.37) displays overshoot in the 2nd and 3rd harmonics and the fundamental builds up faster than any of the others in pipe C. The onset of the aluminium resonator, figure 4.38, is very similar to the 30 per cent pipe metal resonators' onset figure 4.34, having both a similar instability in the lower harmonics and a continuous, steady build up of the fundamental.

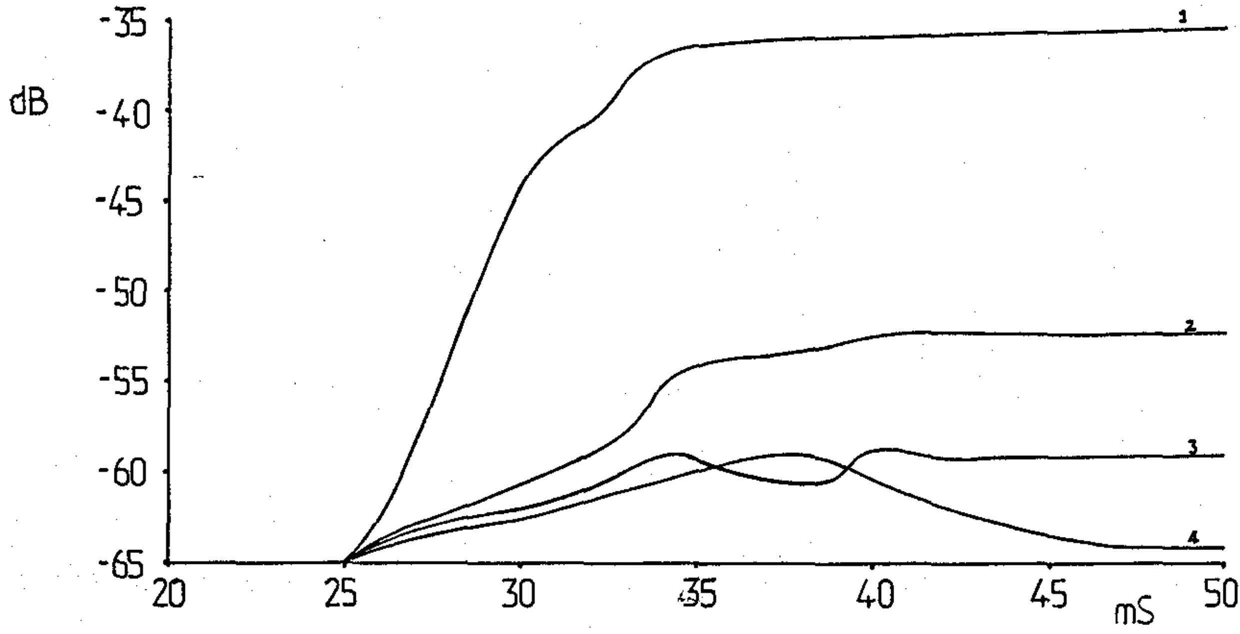

Fig. 4.13 Signal A 1.1 Pipe Metal 0·02 cm.

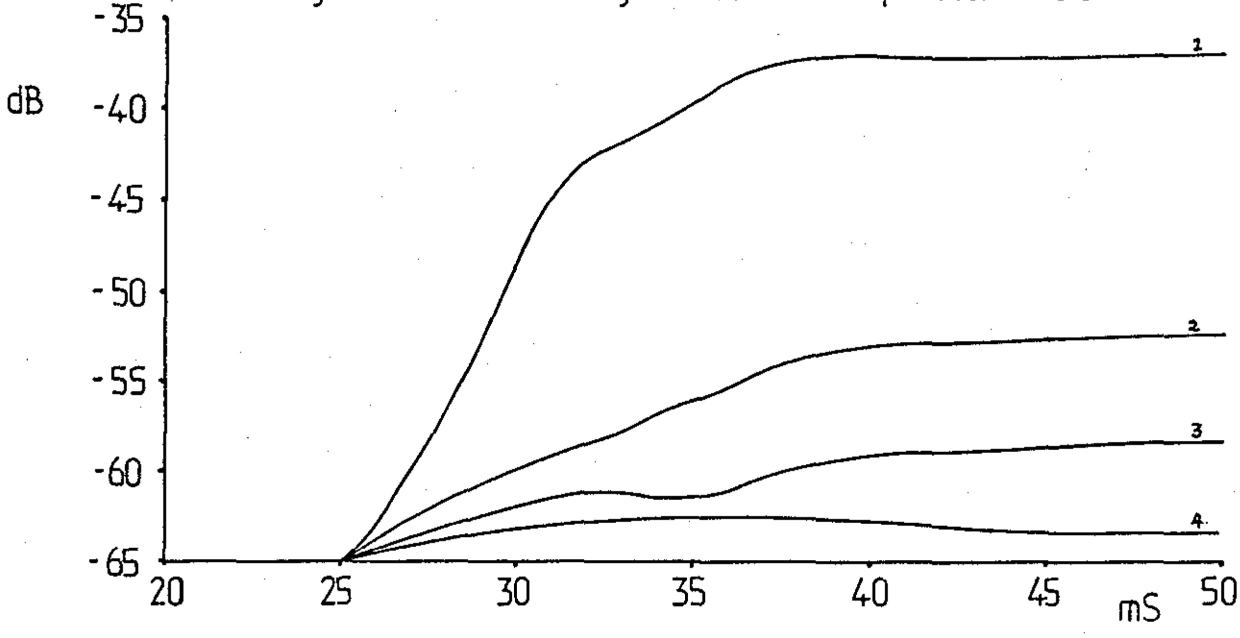

Fig. 4.14 Signal A 1.2 Pipe Metal 0·04 cm.

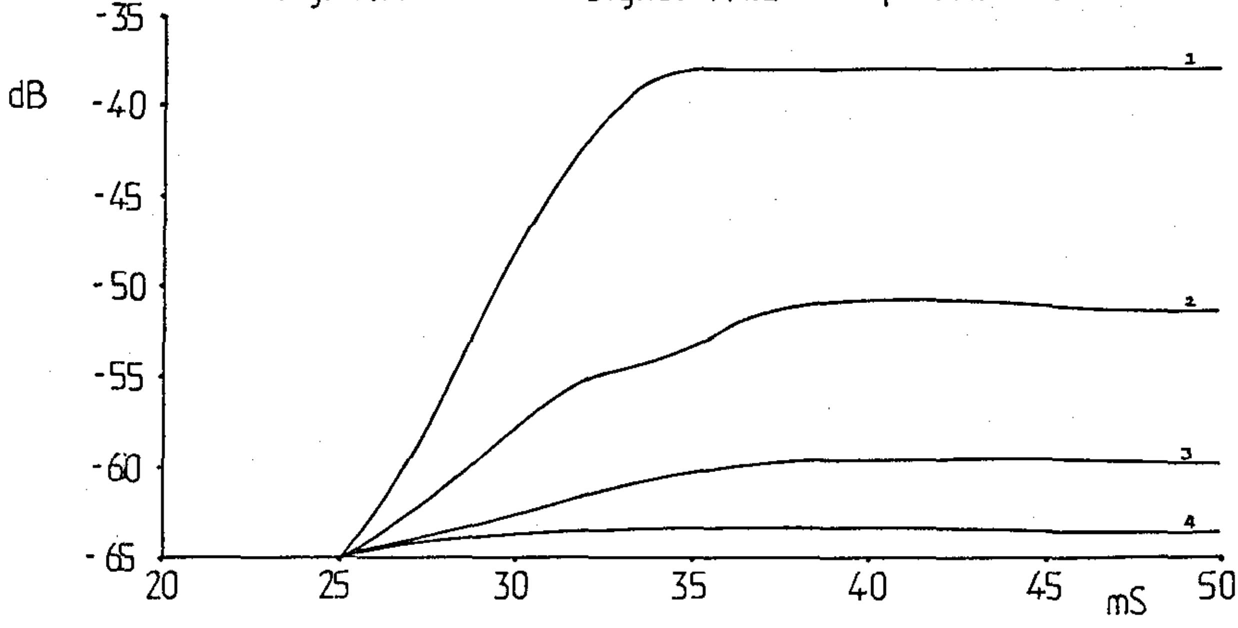

Fig. 4.15 Signal A 1.3 Pipe Metal 0·01 cm.

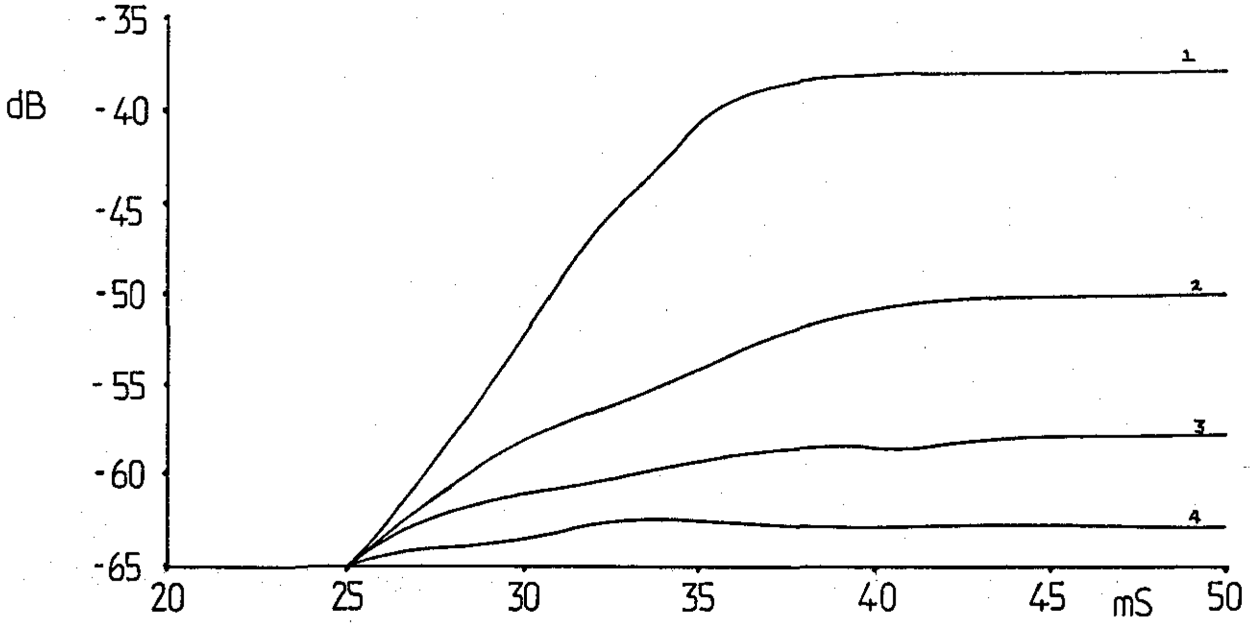

Fig. 4.16 Signal A 2.1 Copper 0·02 cm.

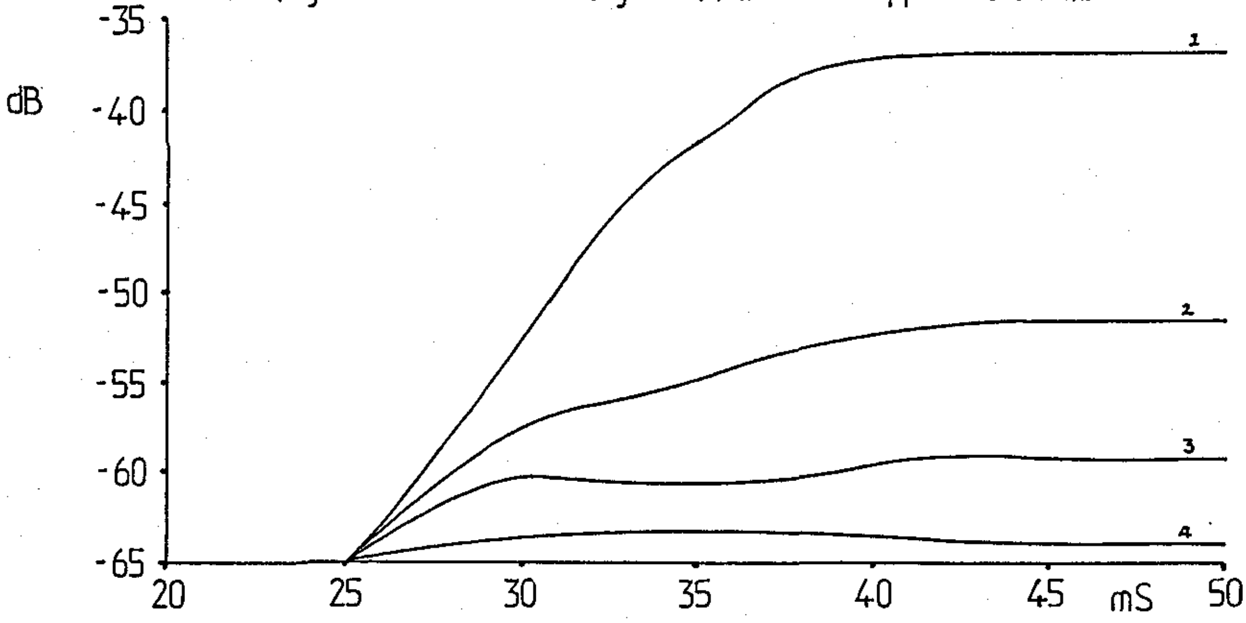

Fig. 4.17 Signal A 2.2 Copper 0·04 cm.

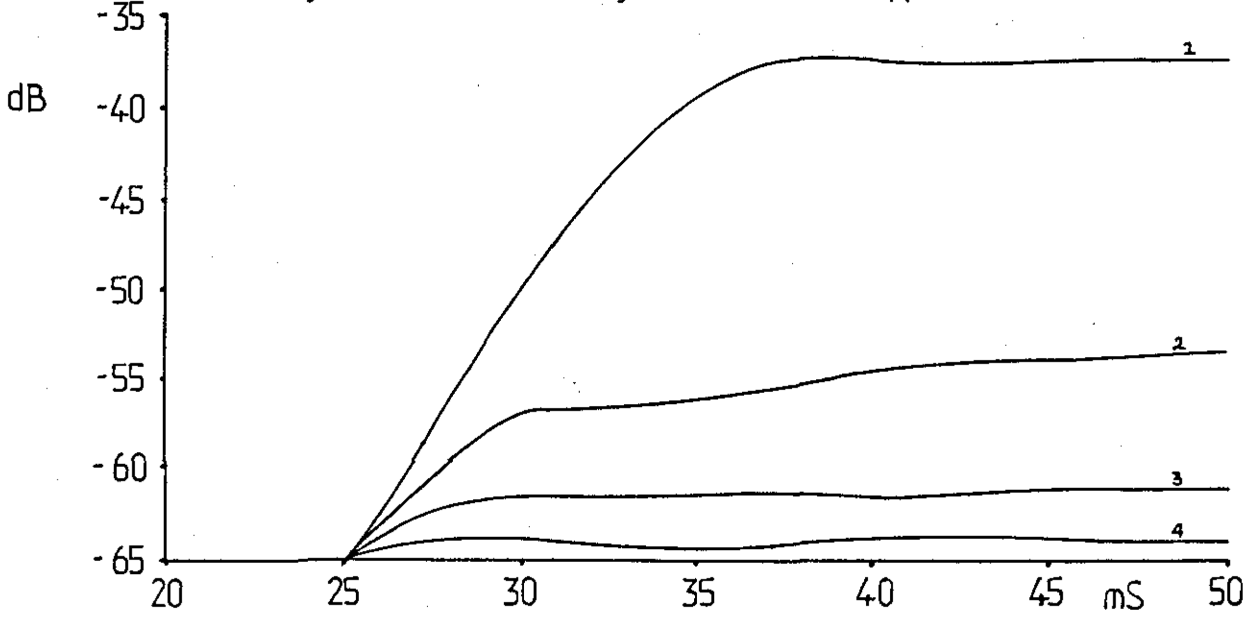

Fig. 4.18 Signal A 2.3 Copper 0·01cm.

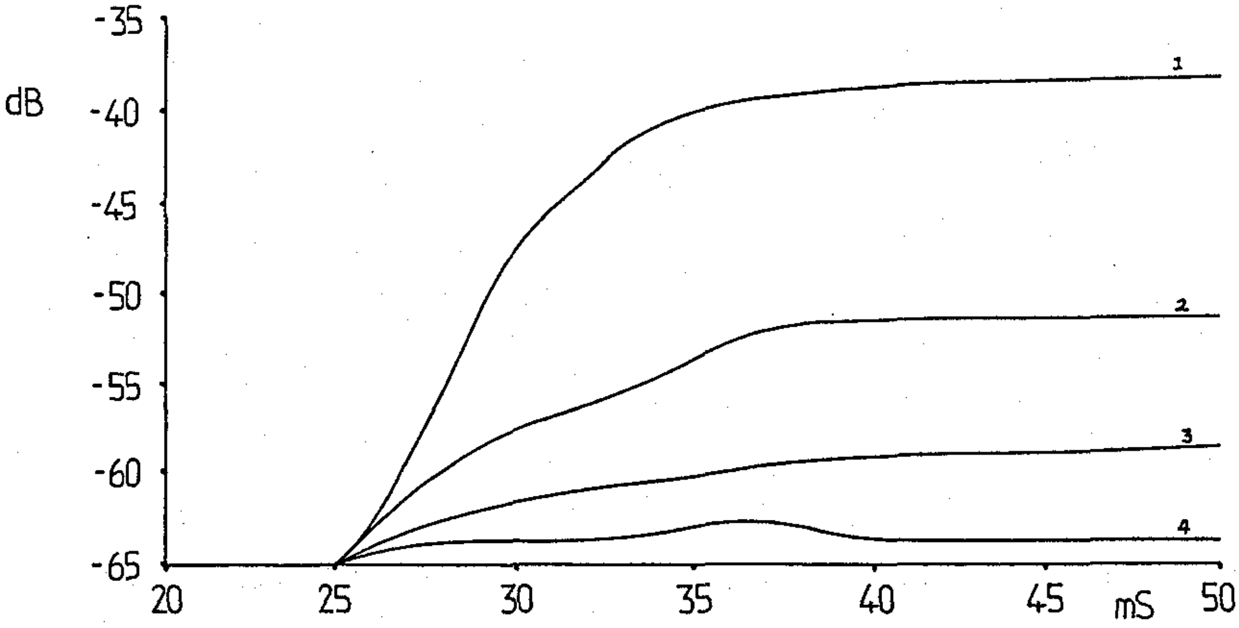

Fig. 4.19 Signal A 3.1 Paper 0·02 cm.

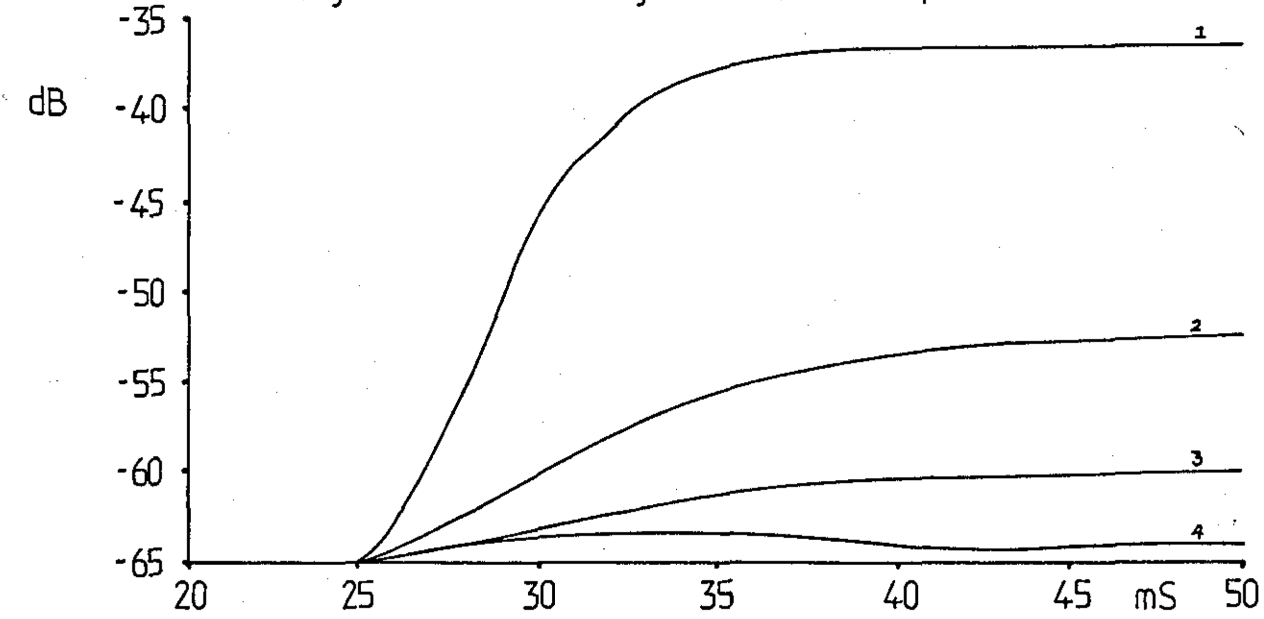

Fig. 4.20 Signal A 3.2 Paper 0·04 cm.

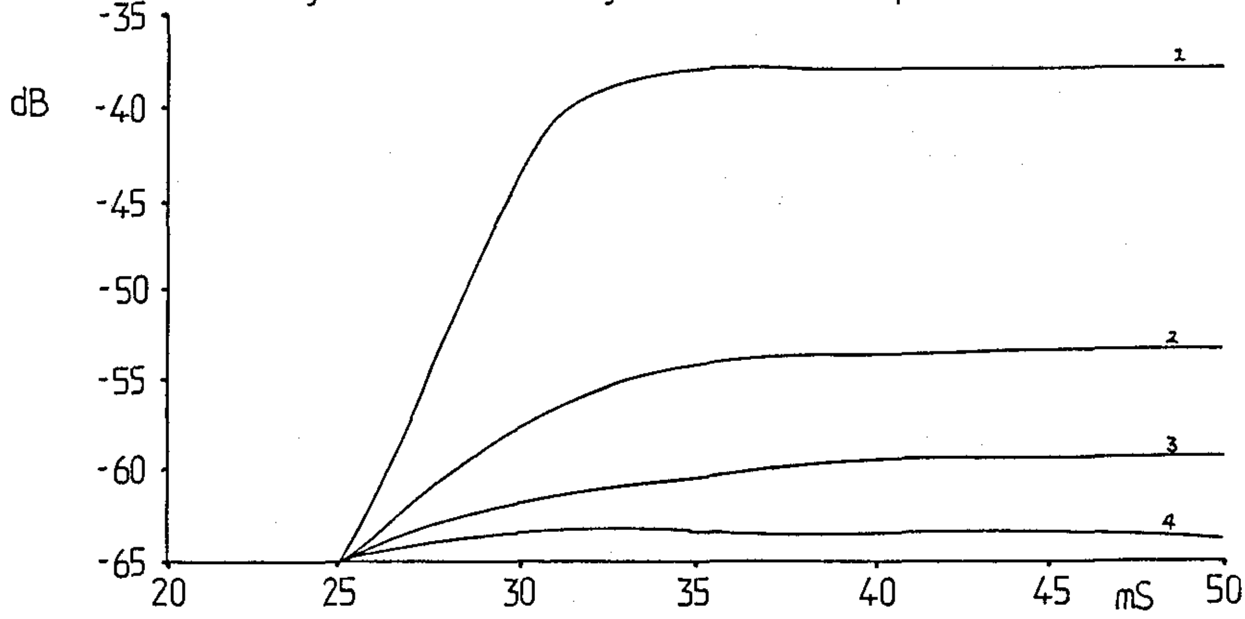

Fig. 4.21 Signal A 3.3 Paper 0·001cm

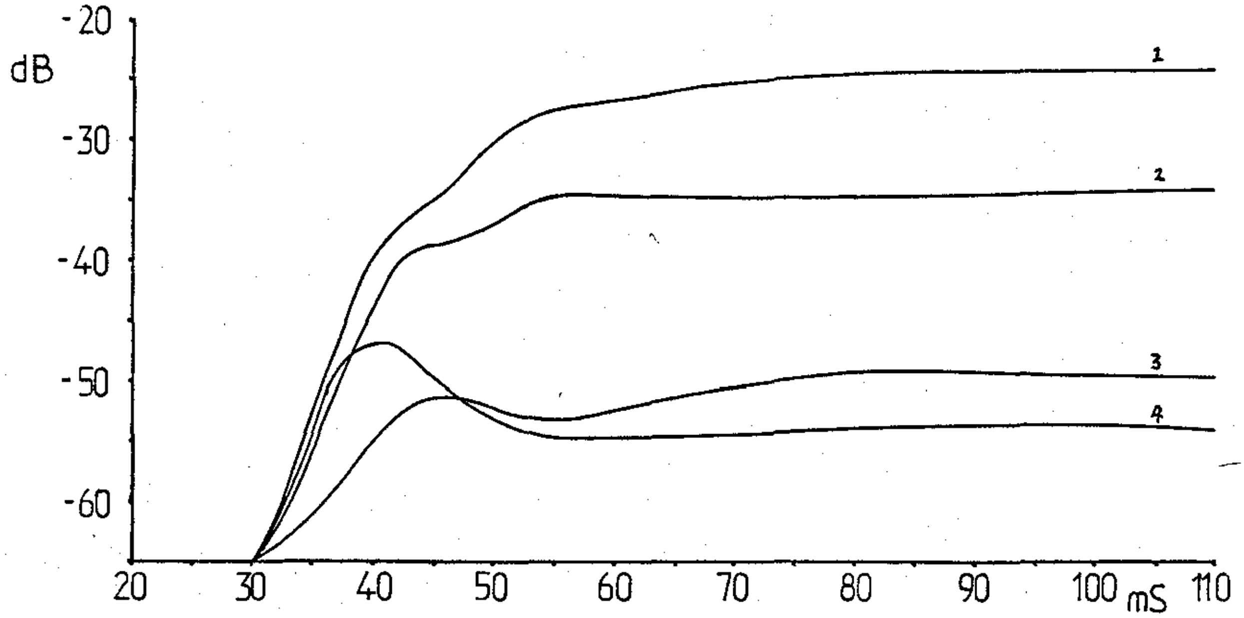

Fig. 4.22 Signal B 1.1 Pipe Metal 0·03 cm.

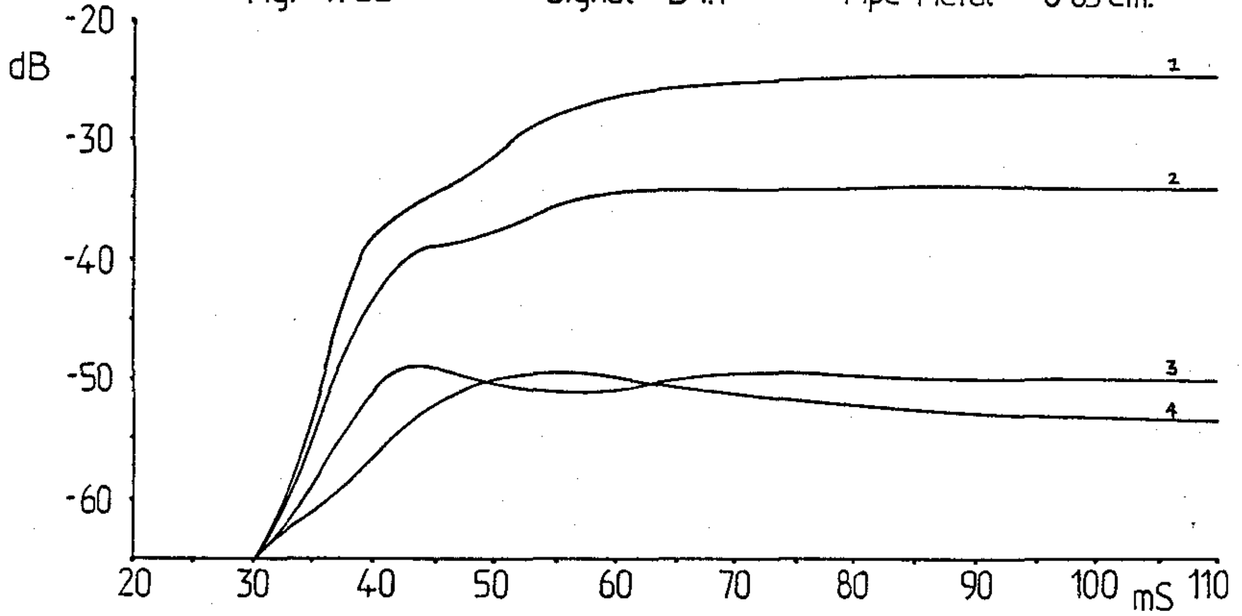

Fig. 4.23 Signal B 1.2 Pipe Metal 0·056 cm.

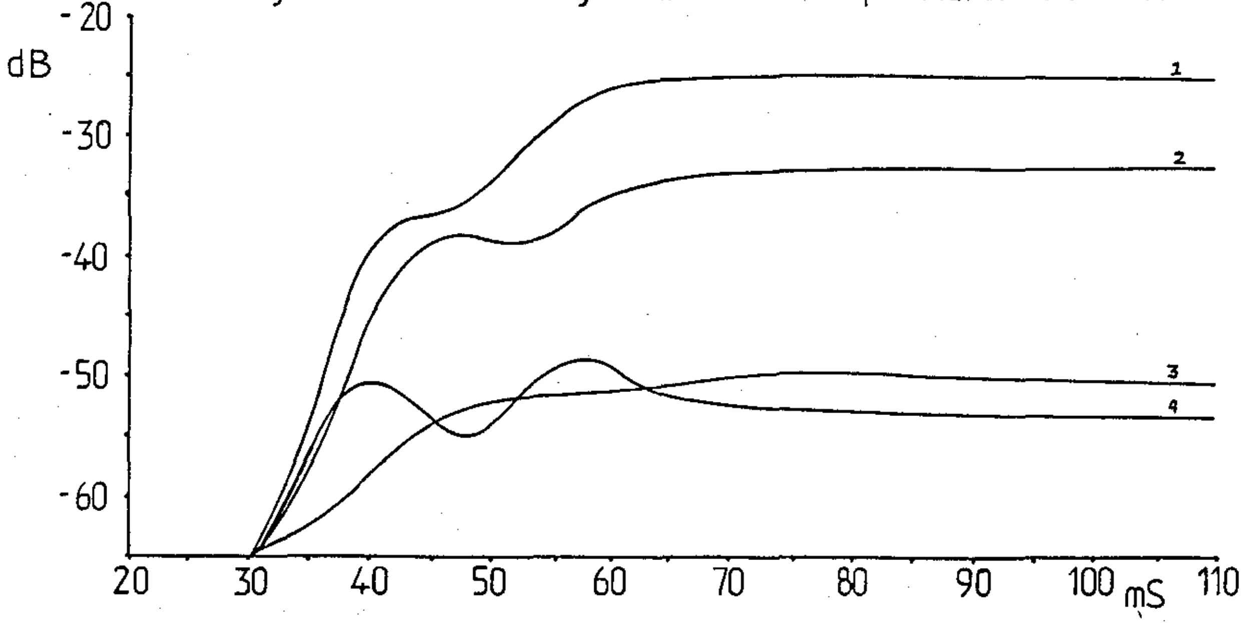

Fig. 4.24 Signal B1.3 Pipe Metal 0·163 cm.

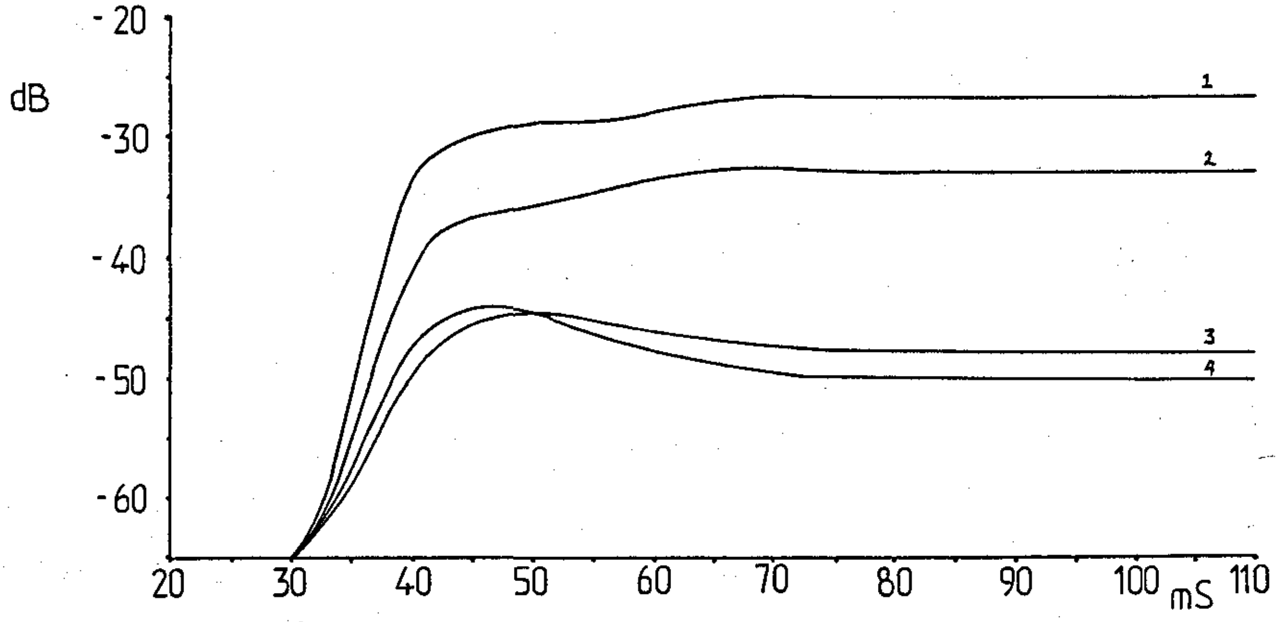

Fig. 4.25 Signal B 2.1 Copper 0·03 cm.

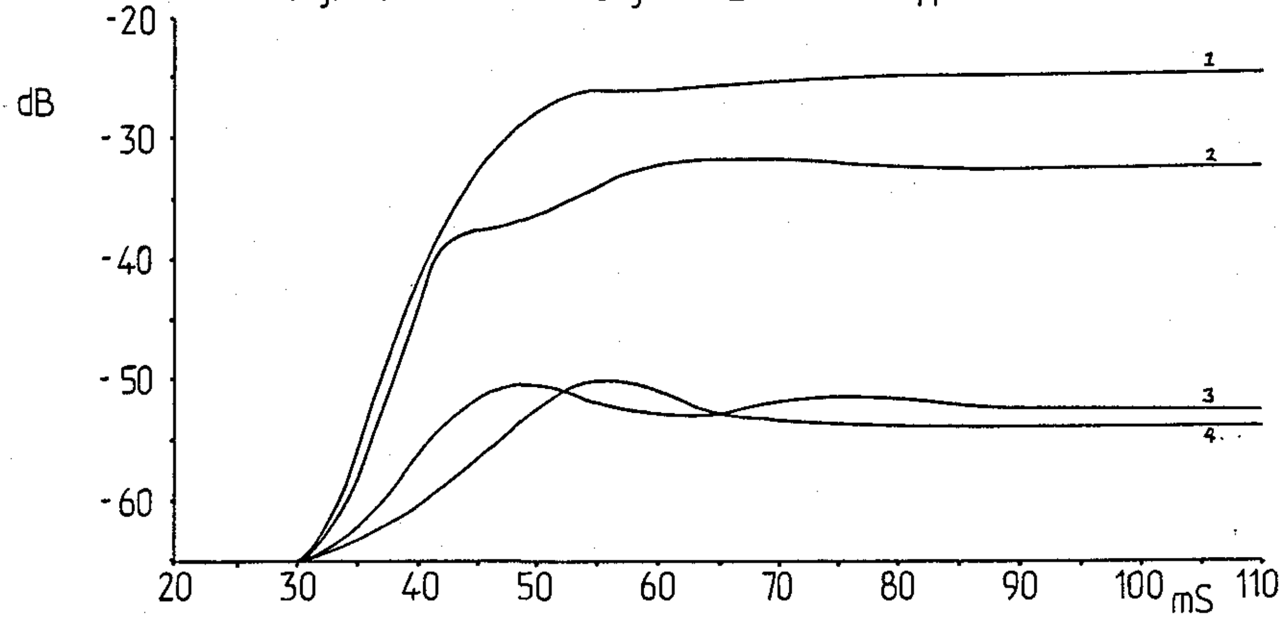

Fig. 4.26 Signal B2.2 Copper 0·056 cm.

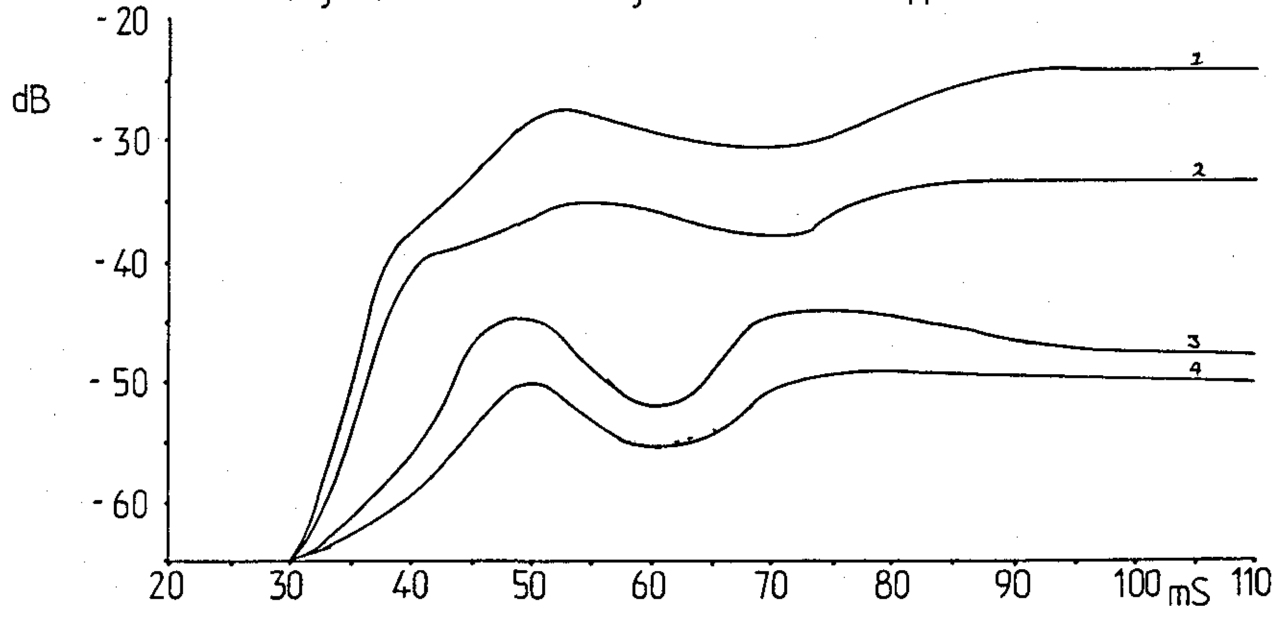

Fig. 4. 27 Signal B 2.3 Copper 0·163 cm.

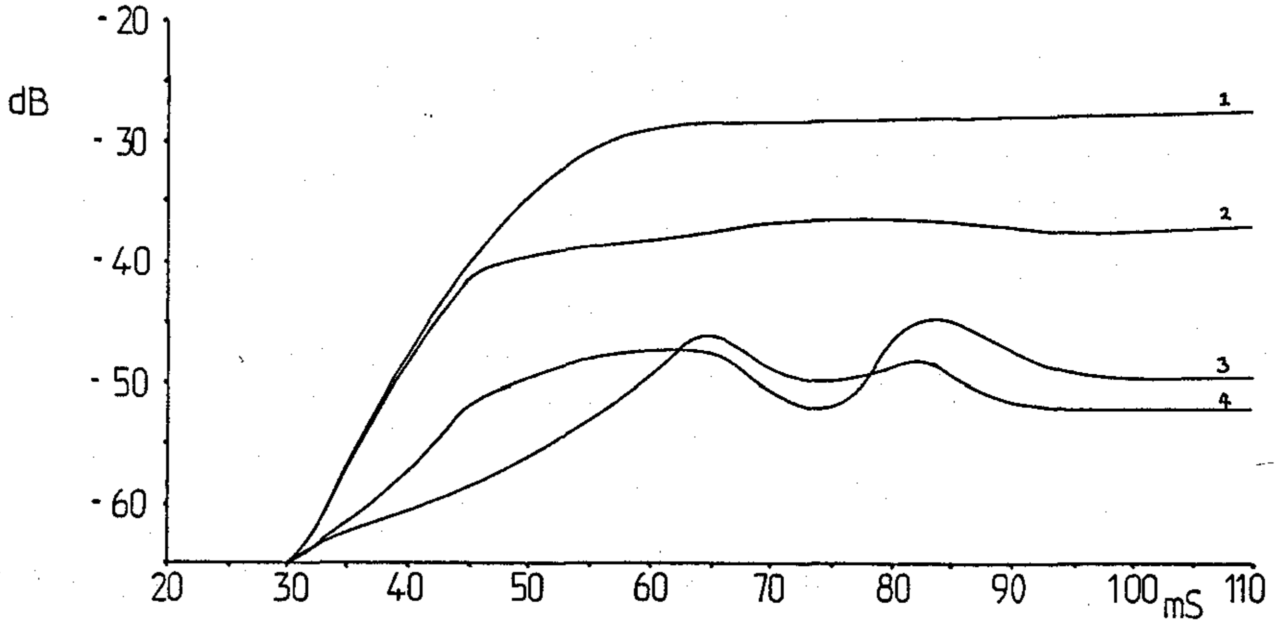

Fig. 4.28 Signal B 3.1 Paper 0·03 cm.

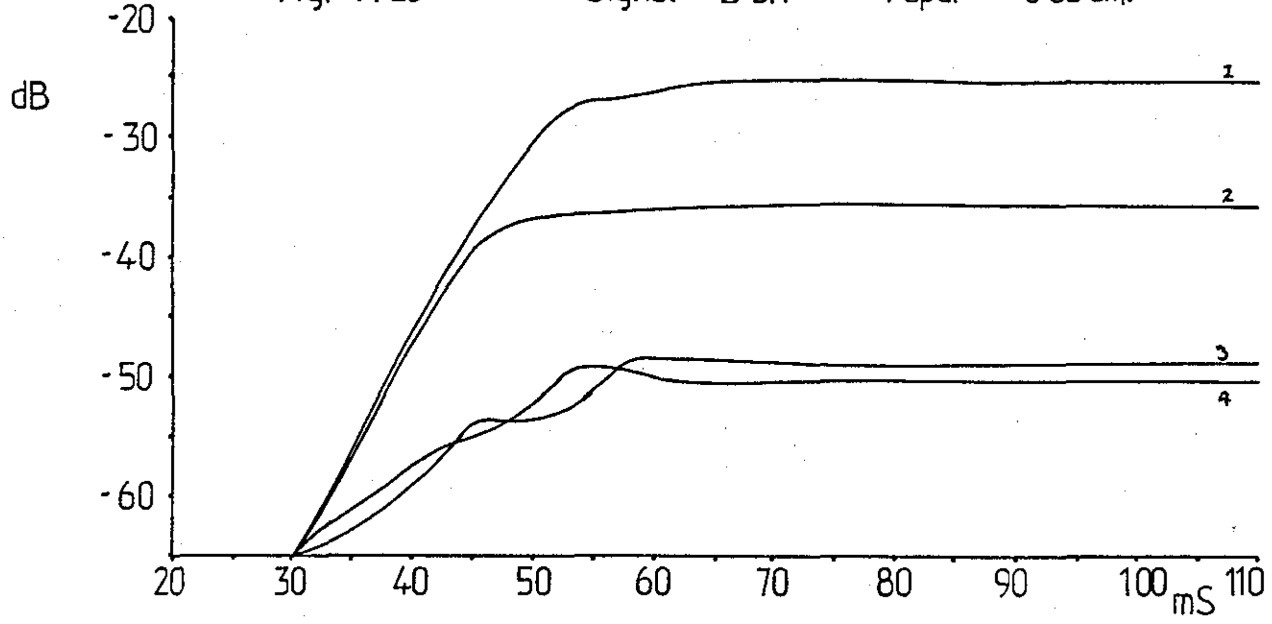

Fig. 4.29 Signal B 3.2 Paper 0·056 cm.

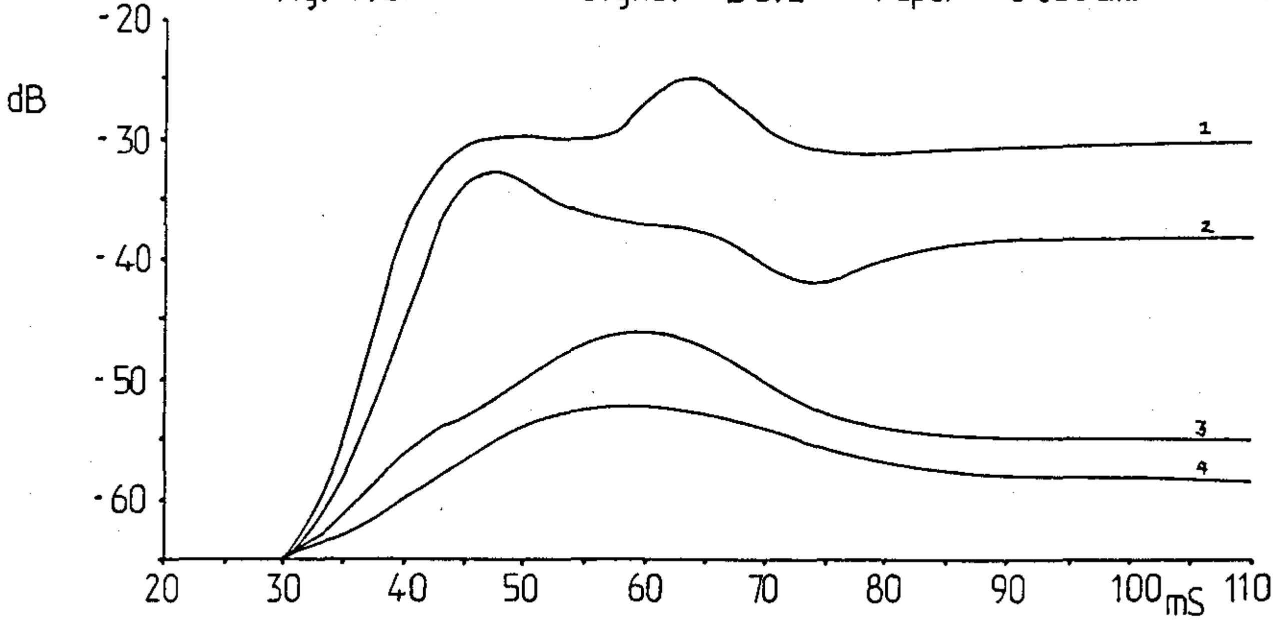

Fig. 4.30 Signal B3.3 Paper 0·163 cm.

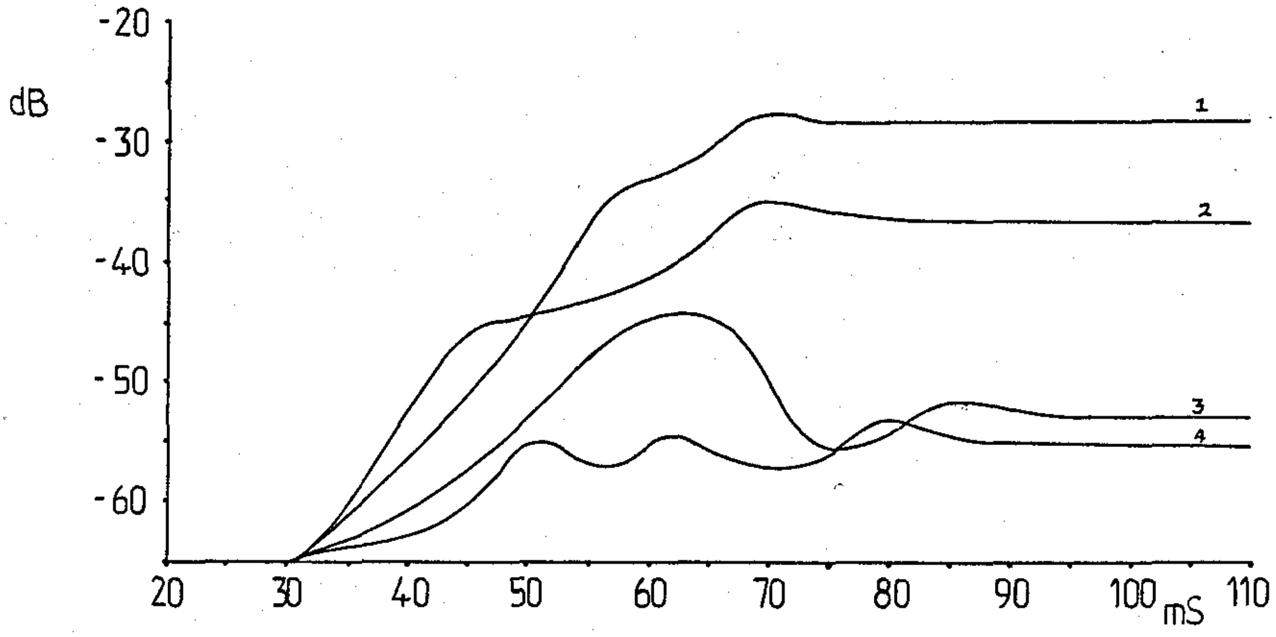

Fig. 4.31 Signal B4.1 Steel 0·163 cm.

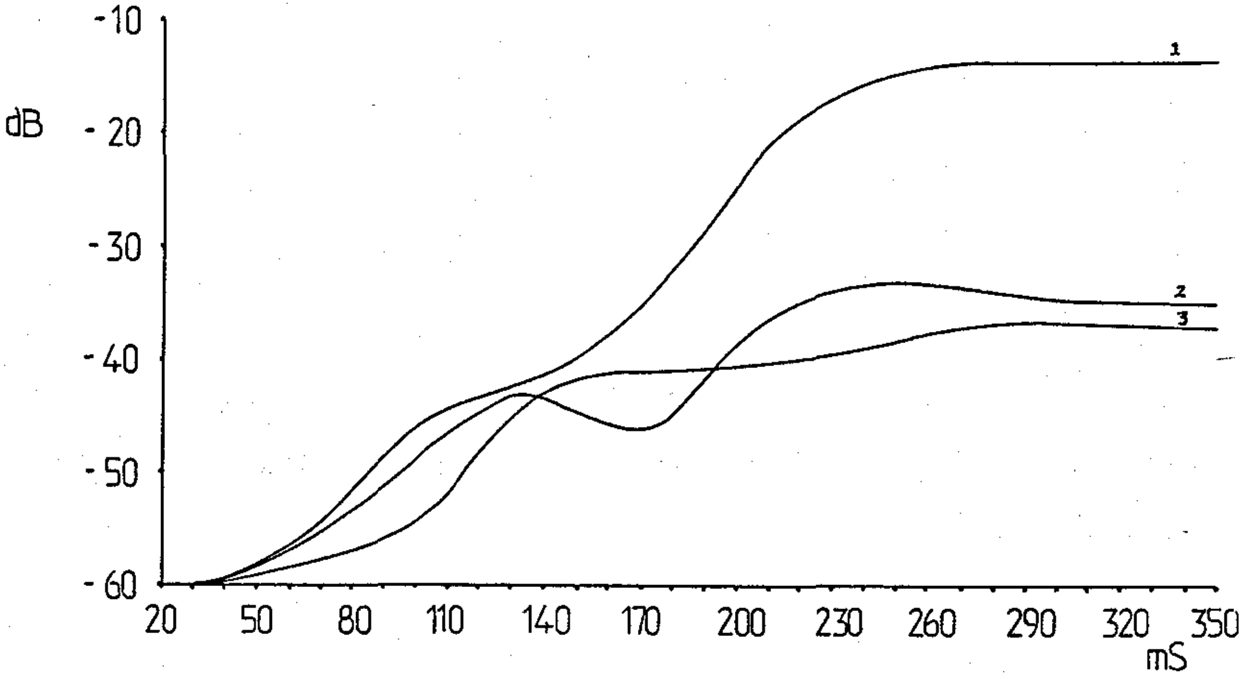

Fig. 4.32 Signal C 1.1 70pc Pipe Metal 0·07cm.

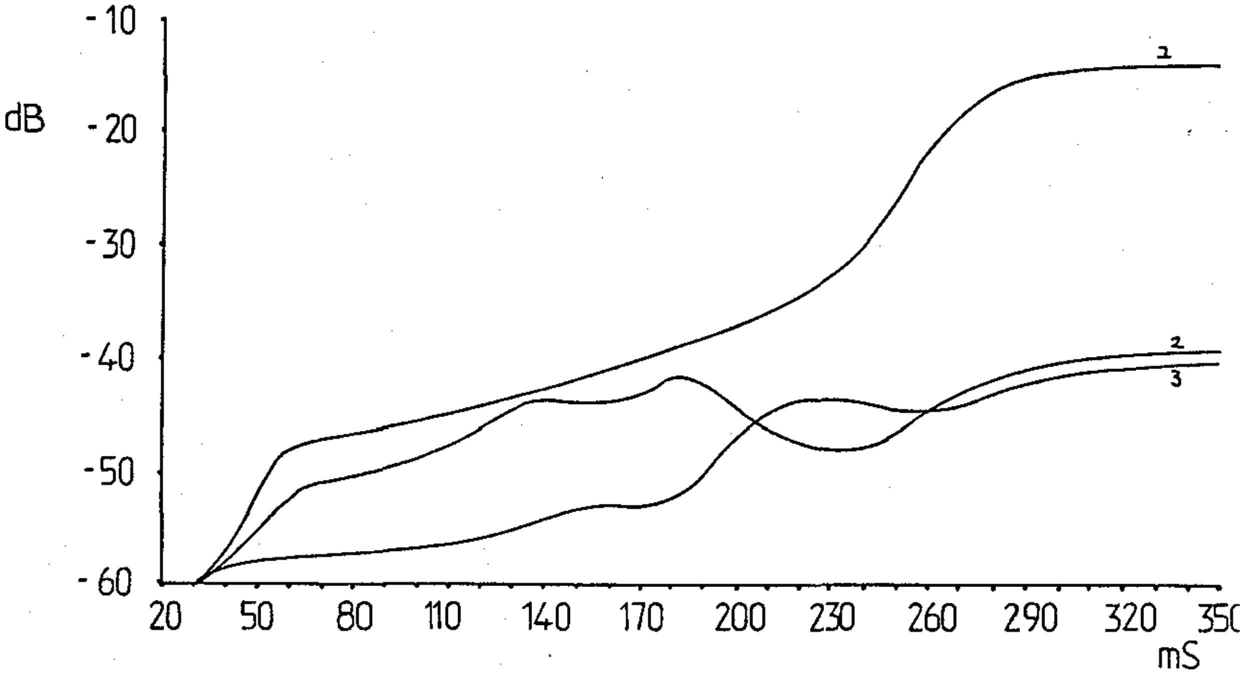

Fig. 4.33 Signal C 1.2 70pc Pipe Metal 0·12cm.

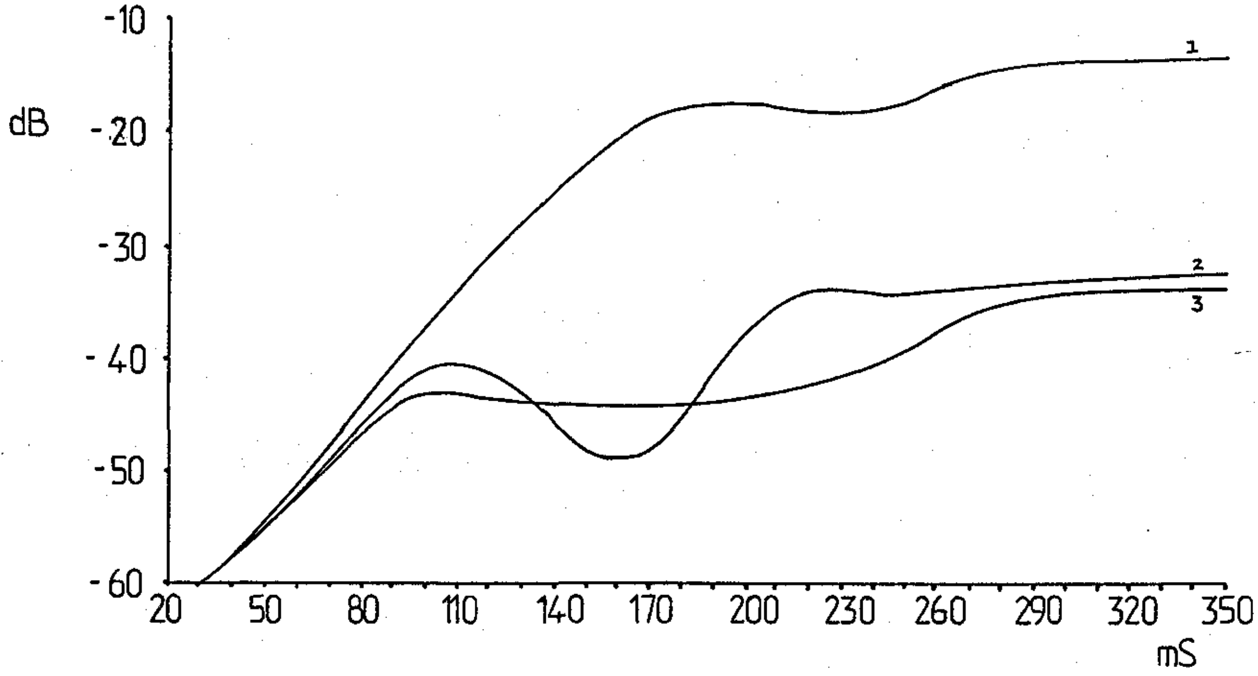

Fig. 4.34 Signal C1.3 30pc Pipe Metal 0·98cm.

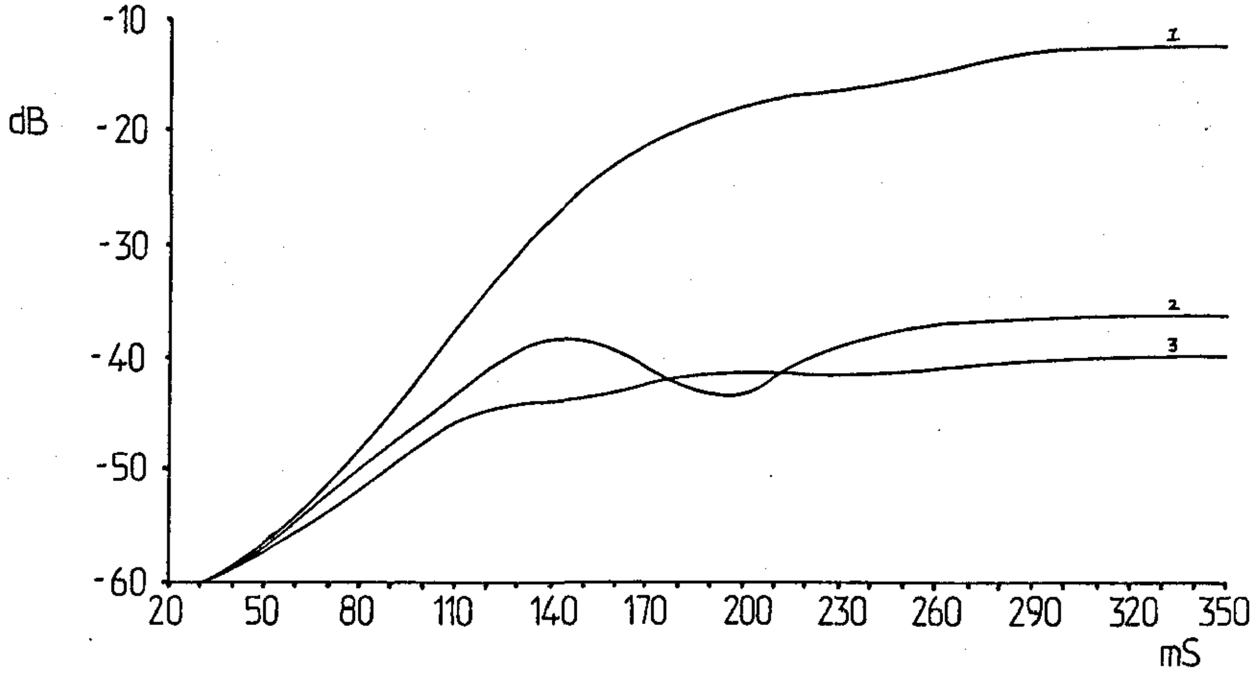

Fig. 4.35 Signal C1.4 30pc Pipe Metal 0·105cm.

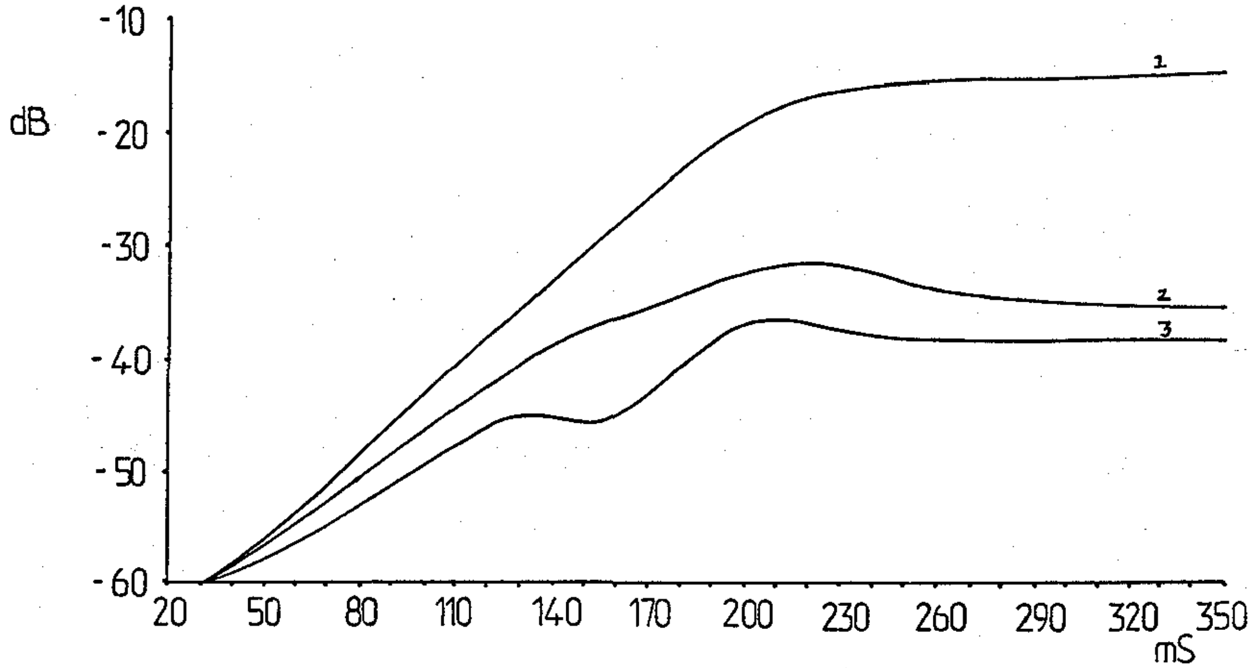

Fig. 4.36 Signal C 2.1 Copper 0·163 cm.

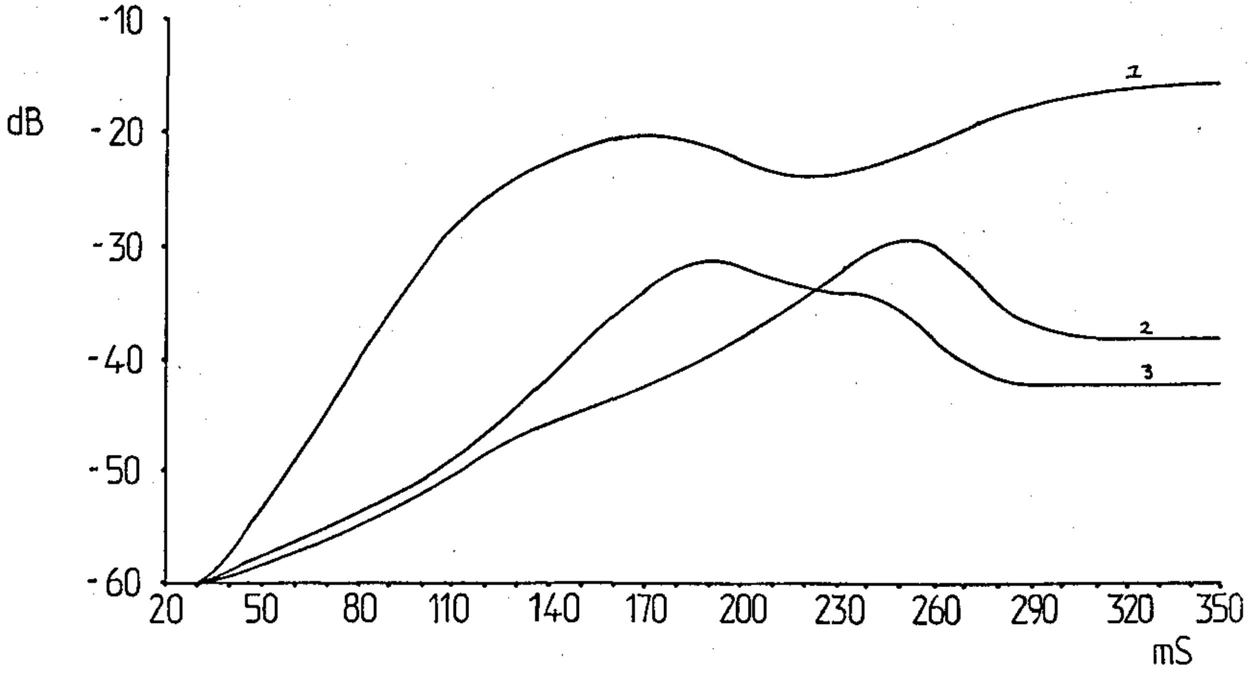

Fig. 4.37 Signal C 2.2 Copper 0·1016 cm.

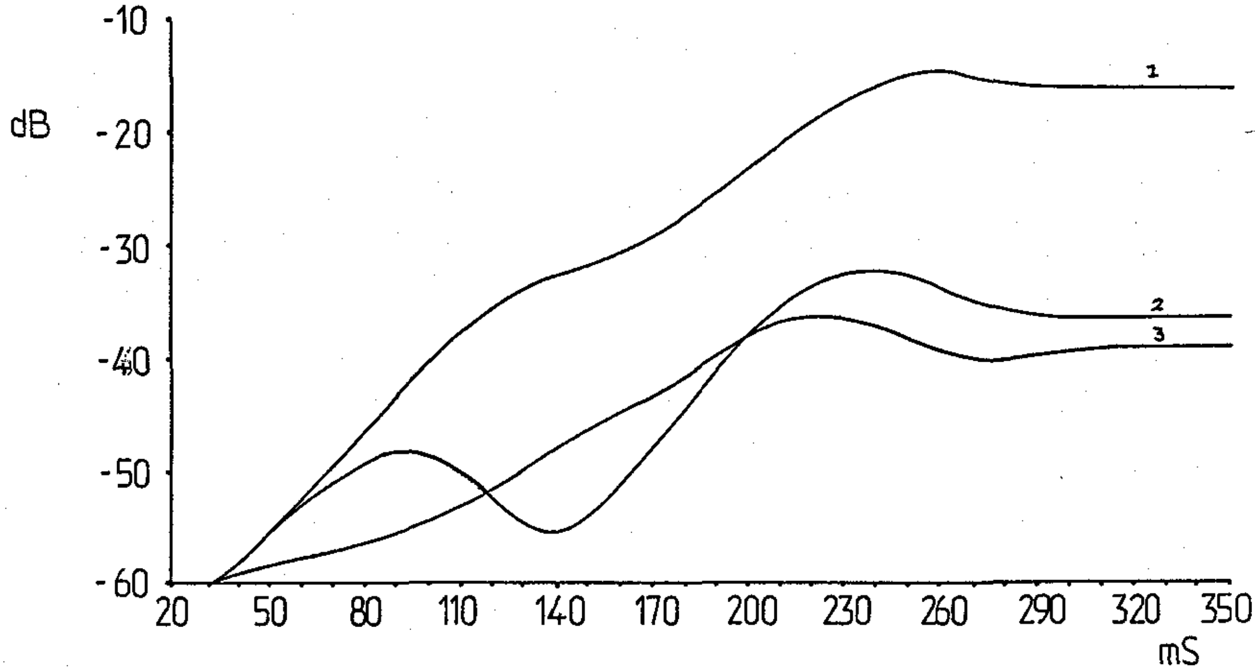

Fig. 4.38 Signal C 3.1 Aluminium 0·061 cm.

4.5.3.3 Discussion

In the comparison of the onsets produced from Pipe A, little discernible change is produced either by resonators fabricated in thicker or thinner sheet or by those made of different materials. The duration of this pipe's transient is very short compared with that of the other pipes analysed, and indeed in comparison with the onset duration of many other instruments.[1] Pipe B and pipe C have onsets of 60 mS and 280 mS respectively. The aural significance of the slight differences which are apparent by closer examination of the graphs depends upon human ability to detect changes within a very short signal onset. However, before considering this, it is well to note that because relatively high pitched signals such as this one require comparatively high frequencies to be resolved in analysis ($F_{max.}$), the sample window time must be large (T) in comparison with the sample duration (T_n) and the block size (N) must be small. Thus, the sampling (Δt) of the signal is comparatively poor, slightly less than 16 times for the 2 cycle segments into which signal A was divided. Poor sampling may result in a slight loss of detail on the graphs though it is of course, to some extent, compensated for by the large number of points described on the graphs within a short time period due to the rapidness of the onset and the short period length of the signals' fundamental.

The perception of differences in the onset of pipe A by the human auditory tract is influenced by the delay in recognition time, which is dependent upon frequency, and is about 4 mS for a 2000 Hz fundamental. It also depends on the integration time within which the ear can recognise an acoustical event and formulate an impression of tone colour. Assuming the signal to be heard in a direct sound field and that the pipe is sounded alone and for several seconds - a situation unlikely to occur during performance - the ear will ignore the first 4 mS of the onset and perceive the subsequent change in the harmonics levels as part of an acoustical event which will take about 60 mS to be understood. For changes in this signal's onset to be distinct, the 16 mS of the onset occurring after about 29 mS on the graphs would have to exhibit a marked change. It is not likely therefore, that any of the onsets analysed can be identified as dissimilar even by the keenest ear. It may be concluded that the resonator's material is unimportant for the tone quality of this pipe. The unimportance of precise timbre in high pitched pipes is confirmed by the practice of organ builders, who sometimes make

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[1] Winckel (120) p42

the highest octave of reed pipes from loudly voiced, narrow scaled labial pipes because the sounds are not audibly different and the work involved in making complex lingual pipes is therefore not justified. The ear's judgement at such frequencies is predominantly based on the loudness of sounds only. Another phenomena known to organ builders which justifies this is the unimportance of the position of the languid and upper lip in small pipes. Minute adjustments to these parts in larger pipes produce radical tonal effects, but in small pipes the positioning makes little difference.

The onsets of signal B, though more diversified than those of pipe A, with the exception of B4.1, exhibit a number of similarities. The onsets last between 50 mS and 60 mS and it is not able that the fundamental and 2nd harmonic, which are the dominant components characterising an onset, develop similarly in each instance. As in pipe A, and pipe C also, the final steady state levels are very similar confirming that the effect on the steady tone of resonator material is inconsequential. Pipe B's onsets appear more influenced by wall thickness than by materials. In each case, paper, pipe metal and copper resonators appear to produce a less stable onset as the wall thickness is increased and the thick steel resonator has produced an onset quite unreminiscent of any of the others. The onsets of different materials of similar wall thickness are very similar.

The onset of pipe C lasts approximately 280 mS and can therefore be analysed significantly by the ear. It is interesting that the two 70 per cent tin pipe metal resonators produce similar onsets (figures 4.32 and 4.33) as do the two 30 per cent tin pipe metal resonators (figures 4.34 and 4.35) but that there are clear characteristics between the predominantly tin and lead tubes. The 2nd and 3rd harmonics in all instances are fairly similar, the differences occur in the fundamental. The gradual build up, almost to the steady state level by 170 mS, in the 30 per cent tin resonator's onset contrasts with the fairly rapid initial rise, followed by a more gradual rise producing a flat curve on the 70 per cent pipe's graph. The steady level is attained only after about 270 mS. This difference is far greater than that produced by the differences in thickness of pipe metal.

The copper resonator's onsets resemble more those of the 30 per cent tin pipe's than the 70 per cent ones, and as noted in pipe B, the thicker material produces a less stable, though not elongated, onset. Figure 4.38 shows the aluminium resonator's onset which has the same calculated radiation level as the 70 per cent resonator in figure 4.32. The second and third harmonics are very similar but the fundamental's curve in signal C3.1 does not have quite the same flatness as in C1.1 and is somewhere between the effect of the 70 per cent and the 30 per cent tin resonator's.

4.5.4 Summary of Wall thickness/Wall Material Experiments

These experiments show that neither resonator material or wall thickness is of particular consequence for high pitched pipes. They demonstrate that onsets become less stable as the material's thickness increases and confirms that ' steady ' tone is independent of the resonator's material, thus verifying the steady state experiments of section 4.1. Peculiar onsets are associated with different tin - lead alloys which support the findings of experiment 4.3.3. Limited success is claimed for the aluminium tube whose wall thickness was calculated, according to the theory in section 4.4, to produce a sound radiation level through the walls similar to the 70 per cent tin pipe metal resonator.

4.6 Summary

The six experiments described in this chapter furnish information about the tonal implications of wall materials, and the extent to which changes produced by materials can be compensated for by voicing adjustments and by wall thickness scales. It has been found that steady tone is imperceivably influenced by the materials of the pipe resonator walls and that certain tin - lead alloys produce characteristic tone qualities which are not the product of skilled voicing but are innate in the pipes' themselves. Wall material and wall thickness appear to effect tone differently at different frequencies and alternative materials seem viable though lip material may be an important additional tone-influencing parameter. The following chapter further discusses the results, relates them to previous work and empirical knowledge, and puts forward an hypothesis about wall material's influence on labial pipe tone.

Chapter 5

CONCLUSIONS

5.1 Introduction

The results of the experimental work described in Chapter 4 are related in this chapter to the findings of previous researchers and the practices of organ pipe makers, which were reviewed in Chapter 2, to fulfil the original, general objectives of the project. These were threefold:-

1. To relate empirical understanding and practice to analytical and experimental work.
2. To demonstrate the tonal implications for organ pipes of pipe-metal.
3. To investigate the possibilities of fabricating organ pipes in alternative materials.

Six aspects were identified from the survey of literature in Chapter 2 which required further work. Each of these has been considered:-

1. Analysis of organ pipe onset transients.
2. Relating the results of the physical analysis of sounds to the subjective ability to make aural discriminations.
3. Clarification of steady state tone changes attributable to organ pipe resonator materials.
4. Tone influencing relationships between resonator wall material and wall thickness.
5. The extent to which voicing adjustments enable differences in timbre resulting from alternative pipe fabrication materials to be corrected.
6. The application of theoretical work by Backus and Hundley[1] to the question of wall material effects on tone.

Points 1 and 2 above, concerning the techniques of transient analysis and the relationships between the results of analysis and auditory ability, were considered fully before experimental work began. Chapter 3 describes a method of onset analysis and relates tonal characteristics to the limitations of man's auditory perception. The remaining areas, which required further experimental work for clarification, were framed in Chapter 4 as the subjects of the experimental programme. Experiments were undertaken to:-

1. Assess the effect of pipe resonator materials on steady pipe tone.

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[1] Backus and Hundley (3)

2. Assess the effect of resonator wall material on onset tone.
3. Assess the effect of resonator wall thickness on onset tone.
4. Show whether voicing adjustments can elicit characteristic onsets associated with pipes made from standard lead/tin alloys from pipes made from tin/lead alloys of different composition.
5. Use Backus and Hundley's theory, which provides a relationship between wall material and tone, to suggest suitable wall thickness for pipes made in other materials.

In the following sections each of the first four points is discussed separately, and subsequently the importance of pipe lip material, whose role is suggested by the results of the experiments, is discussed. Then, the relative influence on pipe tone of lip material, wall material, wall thickness and voicing are discussed and finally, criterion for alternative materials are considered.

5.2 Detailed Conclusions

5.2.1 Material and Steady Pipe Tone

The results of steady-state analysis comparisons between pipes fitted with interchangeable steel and pipe metal resonators discussed in section 4.1 , show that while measureable differences occur in the harmonic spectrum, these are sufficiently random due to unperiodicity of the pipe's sound, even after the onset stage, and are of insufficient magnitude, to be audibly distinguishable. Therefore, subjective perception of steady state tone is uneffected by changes in pipe resonator material.

This is in agreement with Glatter-Götz findings[1] (cf section 2.3.2). In similar experiments he showed that variations in the harmonic-tone-structure among pipes of different materials are similar to the variations found among pipes of the same material. Although their conclusions are uncorroboratory, Lottermoser[2] and Boner and Newman's[3] results also show only slight changes in levels as in the experiment at section 4.2 . The results of this steady state experiment undertaken as part of this project, however, substantiate the conclusions of Boner and Newman rather than Lottermoser, since spectral characteristics associated with particular materials which Lottermoser claimed to find, and which

[1] Glatter-Gotz (46)

[2] Lottermoser (72)

[3] Boner & Newman (15)

he maintains justifies the use of pipe metal rather than zinc, have not been detected.

5.2.2 Resonator Wall Thickness

The result of varying the resonator wall thickness of the three pipes discussed in section 4.5 , (194 Hz, 900 Hz and 2900 Hz) shows that audibly discernable tonal effects are encountered only in the onsets of lower pitched pipes. Variations in the wall thickness of the smallest pipe, Pipe A (2900 Hz), produces no distinctive measureable change in the onset. At lower frequencies, in Pipe B (900 Hz) and pipe C (194 Hz), changes due to increased wall thickness are distinctly measurable. In the case of pipe B, increasing the pipe wall thickness effected the onset significantly, giving rise to instability during the rise-time of each harmonic. The solitary steel resonator, B 4.1 (fig. 4.31), is a more extreme example, and comparison of the two copper resonators C 2.1 and C 2.2 (figs. 4.36 and 4.37) shows that material also effects tone at this frequency. However, the influence of wall material on perceived tone at lower frequencies is apparently less, possibly due to acoustical peculiarities in the pipes but more likely because of the fall-off of auditory ability.

Justification for the assumption that wall thickness becomes audibly less important as frequency falls below about 200 Hz is found in the practice of making the pipe-metal pipes in a stop 'run-out' towards the lower end into ones made in zinc and sometimes wood. (cf section 2.4) One organ pipe manufacturer[1] states that all their pipes longer than 4 ft. (c 132 Hz) are made in zinc. This is common practice. Although the pipe metal pipes in the middle keyboard region have carefully graduated wall thickness which entails a considerable amount of time spent planing metal, - a difficult task in the case of high-percentage tin metals which it is unlikely would be undertaken if there was no tonal necessity - below the 'break frequency' pipes are made from zinc sheets supplied in standard guage thickness. Sincethe wall thickness of the zinc pipes can not be scaled as in pipe-metal stops, and audibly it is not possible to detect where the pipes change from pipe metal to zinc or wood ones. It is apparent that wall thickness becomes less audibly critical below the frequency where the change occurs. Experiments to verify this and to

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[1] F Booth and Sons Limited

determine to what extent this is due to the decline in auditory ability or if it is an analytically measureable phenomenon could not be undertaken in this study due to the limitations of the anechoic room in which the pipes were sounded. (cf. section 3.3.1)

It appears, therefore, from the experiments, that variations in pipe wall thickness produce audibly discernable changes in the onset tone-quality of pipes over the middle frequency range, approximately 200 Hz to 1100 Hz, and it would seem that wall thickness exerts no perceiveable change in tone on pipes below c 132 Hz.

A secondary point, concerning minimum wall thickness, emerges from these experiments. The transient of the thinnest paper resonator, B 3.3 (fig. 4.28), is dissimilar to the other onsets of pipe B; the 3rd and 4th harmonics are unsteady even after 80 mS. Presumably, this tube's wall is close to the minimum thickness sumised in section 2.5.4.1, at which the body of the pipe is vibrated by the standing wave. This is probably a marginal instance of the phenomenon which is well known empirically.

5.2.3 Resonator Wall Material

Neither wall material nor wall thickness affected the onset of the 2900 Hz pipe A either audibly or measureably. Possibly due to the shortness of the onsets of such tiny pipes and the poor resolution of the hearing mechanism, wall material probably has little perceivable effect on the tone quality of pipes above about 800 Hz. This is borne out by the practice of constructing the top octave of some reed pipes from loud flue pipes, because the tonal effect is insufficiently discernible by the listener to justify the complex and time consuming construction of lingual pipes. (cf. section 2.4)

Comparison of the results for the original pipe metal resonator belonging to pipe B, signal B 1.2 (fig. 4.23), and those of similar wall thickness made in copper and paper, B2.2 and B3.2 respectively (figs. 4.26 and 4.29), reveal, by the similarity of the graphs, that resonator material has little effect on the measured tone of this 900 Hz diapason. Also similar are the onsets of the thinner walled pipe metal and copper resonators, B 1.1 and B 1.2 (figs. 4.22 and 4.25).

At lower frequencies materials have a significant effect on tone as is shown in the results of pipe C. Comparison of the 70 per cent tin resonators (figs. 4.32 and 4.33) with the 30 per cent tin resonators (figs. 4.34 and 4.35) reveals well differentiated onset curves apparently due to the change in material, which are quite independent of wall thickness. The chief, and possibly the only physiologically discernable feature to change, is the onset of the fundamental. The rich tin alloy has produced, in each instance, a less rapid rise curve than the faster onset produced either by the predominantly lead pipe alloy resonator, or those made in copper or aluminium. (figs. 4.36 to 4.38).

The same established practice, cited to suggest the unimportance of wall thickness in low pitched pipes, also justifies the unimportance of wall material in such pipes. The use of zinc for pipes below 132 Hz shows that at this pitch lead/tin alloys contribute no audibly detectable quality to pipe sound.

5.2.4 Tonal Peculiarities Induced by Lead-Tin Alloys

From the results of voicing experiment 2, section 4.3.4, it is possible to affirm that different alloys of tin and lead are responsible for certain highly characteristic labial pipe onsets, thus providing a reason for the selective use of certain alloys for particular stops by organ pipe makers. As has been shown, wall material and wall thickness are of little importance for small, high pitched pipes - those above approximately 800 Hz - and below about 120 Hz these parameters are once again of limited importance at least physiologically, even if measureable differences in spectra could be detected. The results of the two 500 Hz pipes made for voicing experiment 2, which each have resonator and foot made in the same material, reveal a characteristic plosive onset associated with a pipe fabricated in 70 per cent tin which contrasts with the more pedestrian onset of the 30 per cent tin pipe. These results were independent of voicing considerations, as such adjustments were unable to produce the tone of the other pipe from either of the pipes under consideration. Bearing in mind also the characteristic onsets of the 194 Hz pipe C, found in section 4.5, it is reasonable to assume that such characteristics are found among all the pipes in the range approximately 120 Hz to 800 Hz and to agree therefore with what organ builders have maintained avidly, that pipe metal is important in forming the tone quality of certain organ pipes.

The most notable feature attributable to pipe metal is the novel onset imparted by the 70 per cent tin alloy. At present no plausible reason for this is put forward or for the similarity of the levels of sound radiated through the walls of 30 per cent and 70 per cent pipes when wall thickness and resonator diameter effects of pipe scales are taken into consideration. (section 4.4).

5.2.5 Discussion of the Role of Lip Material

The technical and experimental problems involved in investigating the influence of pipe lip materials on tone quality have been discussed in section 3.3 and because of the difficulties, this factor has not been a subject of this investigation. However, various of the experiments carried out indicate that lip material is an important tone-influencing factor.

The extent to which characteristic onsets such as that noted in the 70 per cent tin pipe of voicing experiment 2, are due to the material of the pipes' resonator or to the material of the lip, merits further investigation, for changing the resonator material of pipe B did not influence the onsets, and the onset of the high per centage tin resonators mounted on the low tin foot of pipe C was not as plosive as would be expected. However, the 220 Hz aluminium pipe with 70 per cent tin pipe metal lips, fabricated as part of the experiments relating to Backus and Hundley's sound radiation theory, section 4.4.2, after it had been voiced produced an onset audibly similar to those associated with 70 per cent tin pipes. In view of this and the findings of pipe C noted, it would appear that at frequencies around 200 Hz, although resonator wall material can be an important factor, wall thickness and lip material are also critical in influencing tone. The 880 Hz aluminium pipe with 70 per cent tin pipe metal lips was also satisfactory tonally indicating that lip material is important together with wall thickness, which is shown independently of lip material in the results of pipe B, in this frequency range. Further work is necessary but these findings suggest that lip material is of particular importance to tone quality within the middle frequency range.

Whilst malleability is an important feature effecting the choice of lip materials for pipes made in zinc or copper, the use of plain or spotted metal for lip inserts is claimed by organ builders to ex ert a considerable influence on pipe tone quality which again suggests that lip material is important. (cf. section 2.4) It is supposed therefore that lip material becomes more important in the middle and lower frequency ranges down to about 60 Hz, though these comments are certainly speculative and further investigation is needed.

5.2.6 Discussion of the relative influence of the tone effecting Parameters

Finally in this discussion, an attempt is made on the basis of the work undertaken and that reviewed, to assess the influence of each of the tone influencing parameters identified; viz. wall-material, wall-thickness, voicing and lip material. The aim is to suggest a conjectural, though credible exposition of the relative influence of each factor. The discussion is summarised in diagram, fig. 5.1 .

The diagram illustrates the affinity between wall thickness and wall material over the total range of open pipe fundamental frequencies. The bandwidths of the four areas where these two parameters change in their effect on tone, are also marked, together with information about the audibility of the sounds. The number of harmonics individually perceiveable in each area are indicated and also an auditory sensitivity curve which relates to its own scale on the right of the diagram. This curve is intended to summarise the multiplicity of physiological variables, masking, frequency and amplitude limen, rate of perception, smeare etc., discussed in section 3.2.2.2 . The simplification is necessary in order that the diagram is more explicit.

At the extremes of pipe frequency, where auditory sensitivity is poor, wall material is tonally unimportant and may be selected for malleability, economic or aesthetic reasons. Very deep sounding pipes, those in the lowest octave, are not perceived entirely by the ear but partly by the sense of touch. Onsets are very slow; several seconds may elapse before a note is heard from a large, perhaps 30 foot long pipe, with a cross-section of 400 x 300 mm, apart from a windrush sound audible only to those standing very close. The thickness of materials, usually softwood for rectangular pipes and zinc for cylindrical ones, is selected mainly for structural rather than tonal reasons.

It has been noted already that wall thickness and wall materials influence very little the tone of high pitched pipework. Wall thickness becomes increasingly important at intermediate frequencies but

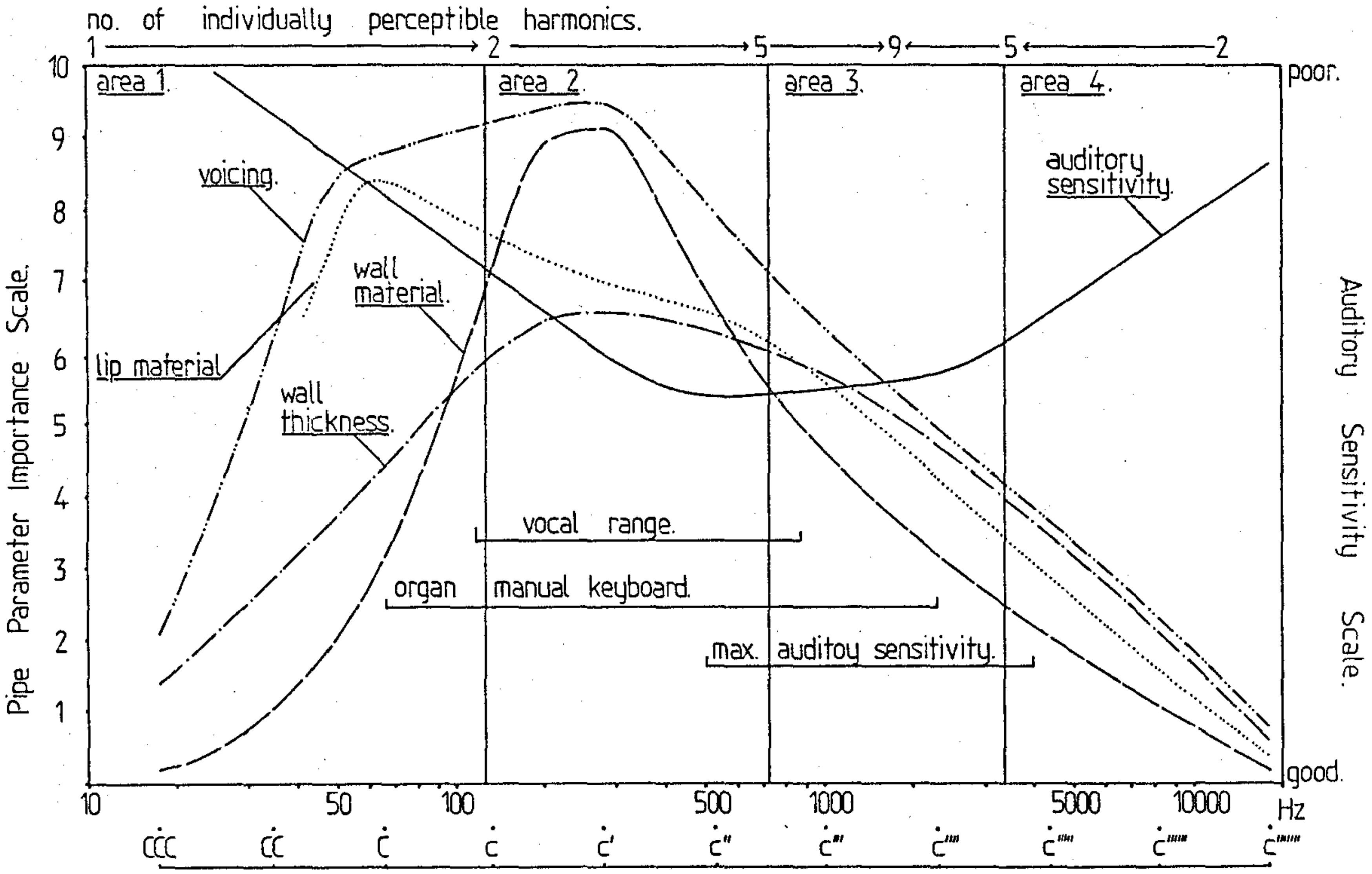

Fig. 5.1 Relative Importance of Pipe Parameters to Organ Pipe Onsets.

seems to exhert less influence than wall material as frequency decreases further, and at the lower end of the organ manual keyboard, around 65 Hz, wall material appears quite unimportant compared with wall thickness.

The pipes in area 4 are all above the unison range of the organ keyboard. Imitative and other characteristic stops are usually found at 8ft. and sometimes at 4ft. pitch. Small pipes form the upperwork stops such as Fifteenth, Larigot and Mixtures, and contribute to the brightness rather than the depth of organ sound. Their rapid onsets give clarity and brilliance, therefore individuality in transients, or highly developed harmonic spectra, are unwanted. The principal variable with these pipes is the overall steady amplitude. Material is unimportant and minimum wall thickness is unlikely to effect tone within the practical range of thickness available. Materials may be selected for malleability and ease of fabrication.

Area 3, in which wall thickness effects the tone and auditory sensitivity is greatest, encompass the whole of the higher part of the organ manual keyboard from about c^2 upwards. The calculations of the sound radiation level differences for extremes of material (section 4.3) suggest that above 880 Hz pipe resonator effects will not perceptibly effect the sound quality; a supposition justified by the use of labial pipes in place of reeds for the c^3 octave of some trumpet stops. It is therefore, unlikely that even towards the low frequency end of area 3, wall thickness effects are particularly noticeable.

It appears therefore, that only in area 2 are resonator effects of practical importance. It is not at all curious that this should be so, as the region coincides with the human vocal range and is therefore, the most played region of the instrument. It is likely that if tonal effects were noticeable only in the 1000 Hz to 2000 Hz octave, for instance, the controversy about materials and tone quality would be less debated as the phenomenon would be less important because it would rarely be noticed. It falls however, in the region where solo stops are found, the only region where organ pipes are normally heard without chorus effects.

Relative to resonator effects, lip material is of less consequence than wall material or thickness for much of the frequency range, though it appears from voicing experiment 2 and from the practice of attaching mouths made of pipe metal to certain lower pitched pipes fabricated in other materials, that the middle octaves are effected as much by lip material as by the material in which the resonator is made.

Below manual pitch, organ builders suggest that the height of the mouth becomes the most important feature. Thus the line on the diagram showing the influence of voicing in the lowest octaves becomes dominant below about 50 Hz. The lip material curve ends at about this frequency as it is impossible to assess the role of this parameter on large, low frequency pipes.

The voicing curve dominates all others throughout the frequency range. Although the range of musically useful tone is limited compared with the tonal changes which can be exerted by voicing, the quality of pipe's sound, stop tone and ensemble colour are so dependent on the preciseness of this operation, that it must be regarded as most important, although it should be noted that the curve is set deliberately close to the others indicating that tone can be altered but not dominated by this adjustment.

Justification has been found from the experiments carried out, from the work of others in this field and from inferences from the practices of organ builders, for the use of certain materials on tonal grounds. It appears from these experiments, that for a limited range of pipe lengths, wall material is important as organ builders have suggested. The perceptibility of the changes to the human listener, however, encompasses a restricted range; through the gradation of wall thickness, which is a feature of pipe-scales, probably perceivably influences tone over a slightly larger range than materials do.

5.2.7 Alternative Materials

From the previous discussion in this chapter it seems that tonal factors are important in the slection of pipe materials in the approximate range 120 Hz to 1100 Hz only. Evidence from organ builders suggests that materials for longer pipes are chosen for mechanical strength and on occasion, for aesthetic reasons. The material used for smaller pipes are apparently chosen formalleability and ease of joining.

As stated elsewhere, (5.2.5) further work is required on the tonal influence of lip materials before alternative materials can be considered properly from pipes in the range 120 to 1100 Hz. However, it has been shown by the results of the two pipes fabricated in aluminium (section 4.4) that within this range pipes made with high percentage tin lip inserts can produce the desired overshoot reminiscent of pipes made in 70 per cent tin pipe metal. It seems likely that wall thickness scales are important in producing satisfactory tone from pipes made in aluminium, though this is also an area in which more research is needed.

Production problems arising from malleability and joining are also factors involved in the selection of alternative materials, though these considerations are beyond the scope of this study.

5.3 Summary of Conclusions

5.3.2 Methodology

i) **Comparisons of the results of steady state and onset analysis by electronic techniques must be related to the sensitivity of human** hearing in order that the range in which sounds are perceived to be similar can be defined. Two factors are involved. Firstly, due to the limitations of auditory perception parameters which make up sounds may be altered considerably before the original and the new sound can be audibly differentiated. Secondly, because of the unsteadiness of the signals under consideration, even during the steady period, and the heterogeneous nature of subsequent onset transients of the same pipe, analysis results are likely to reflect only one of a range of spectra possible from a particular signal. The interpretation of the results in an absolute way is therefore inaccurate and has contributed to the lack of agreement in the conclusions of other workers.

ii) Diapason stops, although they range in tone from narrow scaled string to wide scaled flute, may be defined more precisely in relation to recent developments in 'Classical' pipe voicing. Diapasons from this school are characterised by an audible onset chiff. This, caused by the rapid onset of the 2nd harmonic before that of the fundamental, is a feature attributable, at least in part, to costly, predominantly tin, pipe metal alloys. Classical diapasons should therefore, be studied rather than any other single pipe tone group, since, if the influence of material on the tone of such intermediately scaled pipes is determined, the appropriation of the findings to stops with less sensitive onsets will be straight forward.

iii) Despite the homogeneous nature of organ stops, the tonal spectra varies considerably between the pipes in various octaves. To draw conclusions on an ab uno disce omnes basis is not therefore possible. Representative pipes from various parts of the rank should be involved in experiments.

5.3.2 Tonal Effects of Materials

i) Neither pipe resonator materials nor wall thickness influence the steady state spectrum of labial organ pipes perceivably.

ii) Tonal changes due to resonator wall materials are discernible only in the onset transients of pipes in the approximate range 120 Hz to 900 Hz.

iii) All pipes may be tonally influenced if the wall thickness is insufficient, rendering the pipe's sound useless musically. Only in the range 200 Hz to 1100 Hz does maximum wall thickness effect tone, though, in the lower region of this range, up to about 500 Hz, wall thickness appears to be far less critical than wall material.

iv) Voicing can radically affect the tone of organ pipes. However, within the limits of musically useful sounds, voicing is a process through which a pipe's potential tone quality is achieved and subtley balanced with the other pipes of the same rank to produce stops which combine well.

v) The materials from which pipe lips are made exert most influence on tone in the middle frequency range. It is surmised from pipe making practice that lip material is as important as wall thickness on the range 300 Hz to 1100 Hz and would appear to be the most important single feature effecting the tone of pipes between 50 Hz and 120 Hz.

5.3.3 Selection of Pipe Fabrication Materials

i) The criterion for the choice of pipe materials varies according to the frequency of the pipe. Tonal factors are only important in the selection of materials for pipes in the range of the organ manual keyboard - C to c^4. The materials used for small pipes has no tonal function but is required to be malleable and easily joined. It is surmised from organ building practice that materials are chosen for longer pipes on the basis of mechanical strength and, on occasion, for aesthetic reasons.

ii) Aluminium pipes fabricated with 70 per cent pipe metal lip inserts and sounding frequencies within the critical range, have produced satisfactory onsets audibly similar to those from 70 per cent tin pipes. Wall thickness was calculated according to the relationship described by Backus and Hundley though it is as yet uncertain the extent to which this and lip material influences the tone.

5.4 Further Work

A number of areas for further study are suggested by the conclusions of this work. Further discussion and experiment to show the effect of wall thickness and wall material on pipes longer than those used in the experiments presented here are suggested, and also a study of the practical issues of adopting other materials for organ pipes. Principally, it is necessary to investigate the role of lip materials and lip surface condition as this aspect is manifestly of some considerable tonal importance particularly in the material-sensitive range 120 Hz to 1100 Hz. It is likely that towards the lower end of this range in particular, wall thickness scales become critical for satisfactory tone quality.

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APPENDICES

Appendix A

The Role of Phase Information in the Description of Musical Tone Quality.

This area of research suffered in its early stages from lack of suitable analysis equipment; the work of Konig (1881) and Herman (1894)[1] reached different conclusions using the wave-siren, and after the advent of electronic equipment progress was slow, due to lack of interest since the levels of distortion even in early amplifiers and electro-acoustic transducers - 1932 - were regarded as tolerable. It has also suffered from an over-simplification of Helmholtz' findings and from invidious statements which reflect this misunderstanding. Madsen and Hansen's approach typifies this. They write,[2] "we would like to join sides with those who believe it (phase) to be important and therefore venture to go against Helmholtz....' Although Helmholtz did consider that musical quality was independent of phase, he includes two qualifications to this:[3] firstly, that changes in timbre were not distinct enough to facilitate comparison after the short time had passed which was needed to alter the phases and, secondly, he stated that since harmonics beyond the sixth and eighth give dissonances and beats, it is not impossible that a phase effect does exist and is responsible for this.

Recent considerations of the importance of phase by Plomp and Steenken (1969),[4] which has been largely verified in the work of Madsen and Hansen (1973)[5], established phase to be virtually independent of amplitude in the perception of complex tones. Thus, although when pitch and loudness are changed, the pattern of phase relationships between the partials is disturbed, phase changes may be effected without altering the physiological assessment of the other parameters.[6] This coincides with the idea of several earlier writers[7] that subjective changes produced by variations in phase spectra which leave the envelope of the stimulus invarient, will be small and possibly unperceived. Plomp and Steenken[8] also discovered considerable inconsistency in the ability of individuals to detect phase changes. Averaged over 8 subjects, they state

[1] Madsen and Hansen (76) 7

[2] Madsen and Hansen (76) 2

[3] Helmholtz (50) 127

[4] Plomp and Steenken (96) 409

[5] Madsen and Hansen (76)

[6] Zwicker (132) 238

[7] Zwicker, Flottorp and Stevens (133)

[8] Plomp and Steenken (76)

the maximum possible effect of phase on timbre (the difference in a tone consisting of only sine and cosine terms compared with one having alternate sine and cosine terms) for a fundamental of 145.2 Hz, is equal to the effect of changing the slope of the amplitude pattern by 2 dB per octave. For a 292.6 Hz fundamental the change is less, 1.6 dB per octave, and for 584.8 Hz they state the effect amounts to changing the amplitude slope pattern by only 0.7 dB per octave. Quantitatively, the effect of the maximum change on the perceived sound is, for the 292.4 Hz fundamental, equal to the effect of changing the SPL by 2 dB. This is less for higher than for lower fundamentals. Phase information, although it is calculated by the analysis equipment, is not presented in this study since its role in characterising musical sounds is not clearly defined, and in relation to amplitude, appears of minimum significance from the auditors point of view.

Appendix B

Detail of Analysis Method Adopted, the Design and Operation of Sampling Device.

Introduction

The development of an appropriate analysis technique using the equipment available has formed a major part of this work. Presented here in detail is the method adopted, the application of it to the particular signals involved, the presentation and the validity of the results.

Several methods were considered to analyse the signals. Having found the variable sampling window of the real time analyser to be unsuitable, the Fourier analysis system was used to analyse signals in segments whose duration was defined by the frequency of the signal in its steady state. However, this system was found unsatisfactory due to the assumption of periodicity by the analyser, which is discussed later in this section, and the frequency changes occurring during the transient. Consideration was given to overcoming the difficulties encountered by simultaneously recording the signal together with regular pulses recorded on a separate track of the tape recorder. The duration between these markers would be chosen as an integer multiple of the signal's fundamental frequency. All the recorded information was to be digitalised and the markers used to locate each segment. Analysis could therefore, be performed on segments of the signal without the period boundary problems.

The method, whilst workable, has significant disadvantages over the method finally chosen. The first is due to the frequency changes which occur especially during the onset of musical sounds. These changes, whilst perhaps not producing serious errors, are not taken into account by this method. Secondly, more serious problems could arise from loss of part of the signal due to the limitations of the operation of the A-D converter on the H.P. 5451A Analyser. If the system did happen to become overloaded, the resultant lack of information transferred could provide insurmountable problems and serious errors. A method was sought which could sample the signal allowing only the segment required for analysis at that time to be presented to the A-D converter for analysis.

Sampling Device Description

The signal from the tape recorder is sampled cycle by cycle using the fundamental frequency of the sound itself as a counting pulse. A gated amplifier enables segments to be isolated and subsequently analysed. The samples are chosen by setting initial and final co-ordinates on two thumbwheel switches. (Fig. B1)

A Ferranti 424 amplifier is controlled by inhibiting the current normally present at the chip's gate. The schematic arrangement of the logic by which this switching is effected is shown in figure B2. The numbers selected for the beginning and end of the segment on the two digit hexadecimal switches establish the duration of the sample and how many cycles after the first are to be counted before the sample begins. The incoming signal is filtered to leave only the fundamental. This is applied to the operational amplifier type SN 741 which produces a TTL compatible square wave output and enables the minimum signal level to be adjusted. The Schmitt-Trigger, SN7414, provides further wave shaping. The signal is subsequently applied as the operating pulse to the SN7493 counters. Since the number anticipated to be the largest needed was 193 and the counter chips contain 4-bits each, two are employed giving a total of 8-bits and a maximum count of 512. The counter's outputs are compared with the settings on each of the thumbwheel switches by 8-bit comparitors, SN7485, relating to the switch. Each comparator's output is received by a NOR gate, SN7402, and its signal, after suitable amplification and inversion, provides the necessary pulses for the 424's gate.

The reset circuit sets the counter outputs at zero. A single LED driven from the 4 least significant outputs of the counter monitors this and provides a useful assurance that the counter has in fact reset when the button is pressed and, since the NAND gate 7400 inhibits the counter when A becomes greater than B, the LED indicates that the task has been completed.

The period elapsing after the energising of the pallet valve which allows wind into the pipe foot and the emergence of the first sounds to be analysed is monitored since the speed of the attack often characterises instrument tones, not least the tone of particular organ pipes whose delay in speech can sometimes be the principal characteristic. This period can provide an important feature for comparison and is computed as part of the analysis procedure. It is measured using an electronic Timer-counter set to measure the time-period elapsing between signals applied to the inputs A and B. The counter is triggered on the square wave signal simultaneously recorded with the signal itself but on

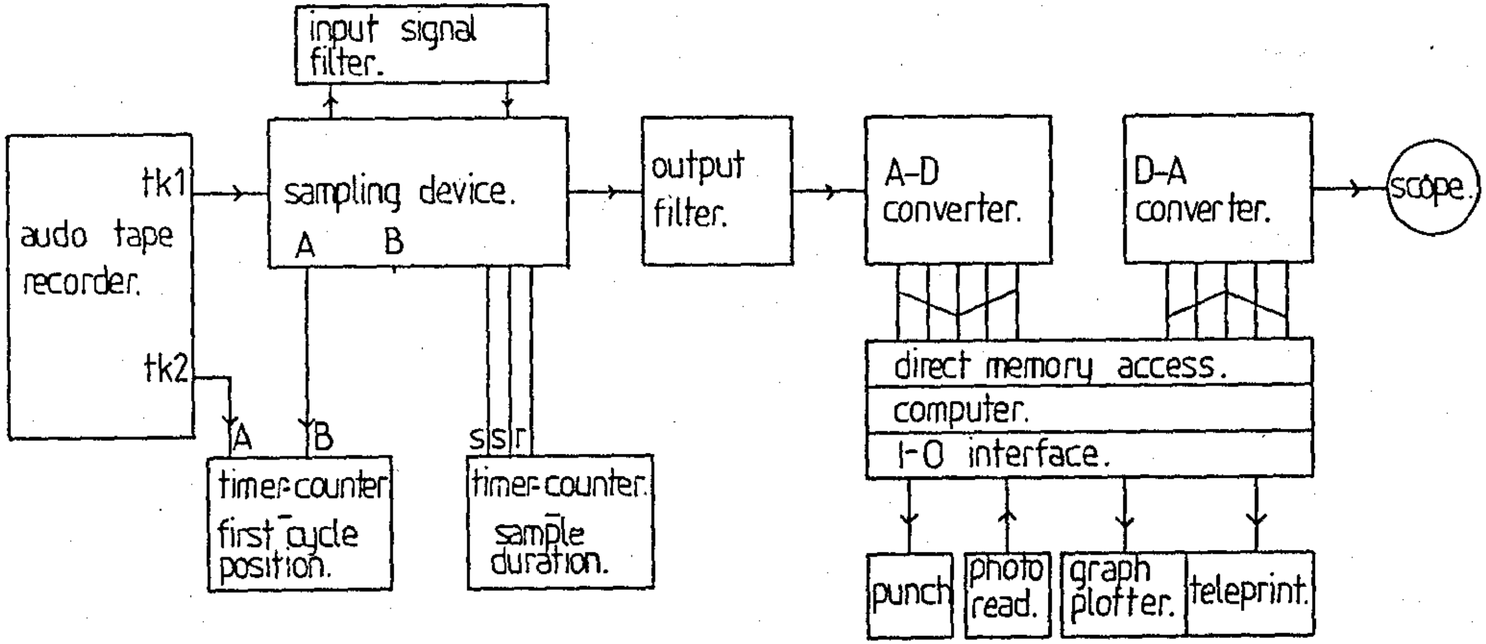

Fig. B1. Schematic Arrangement of Analysis Equipment.

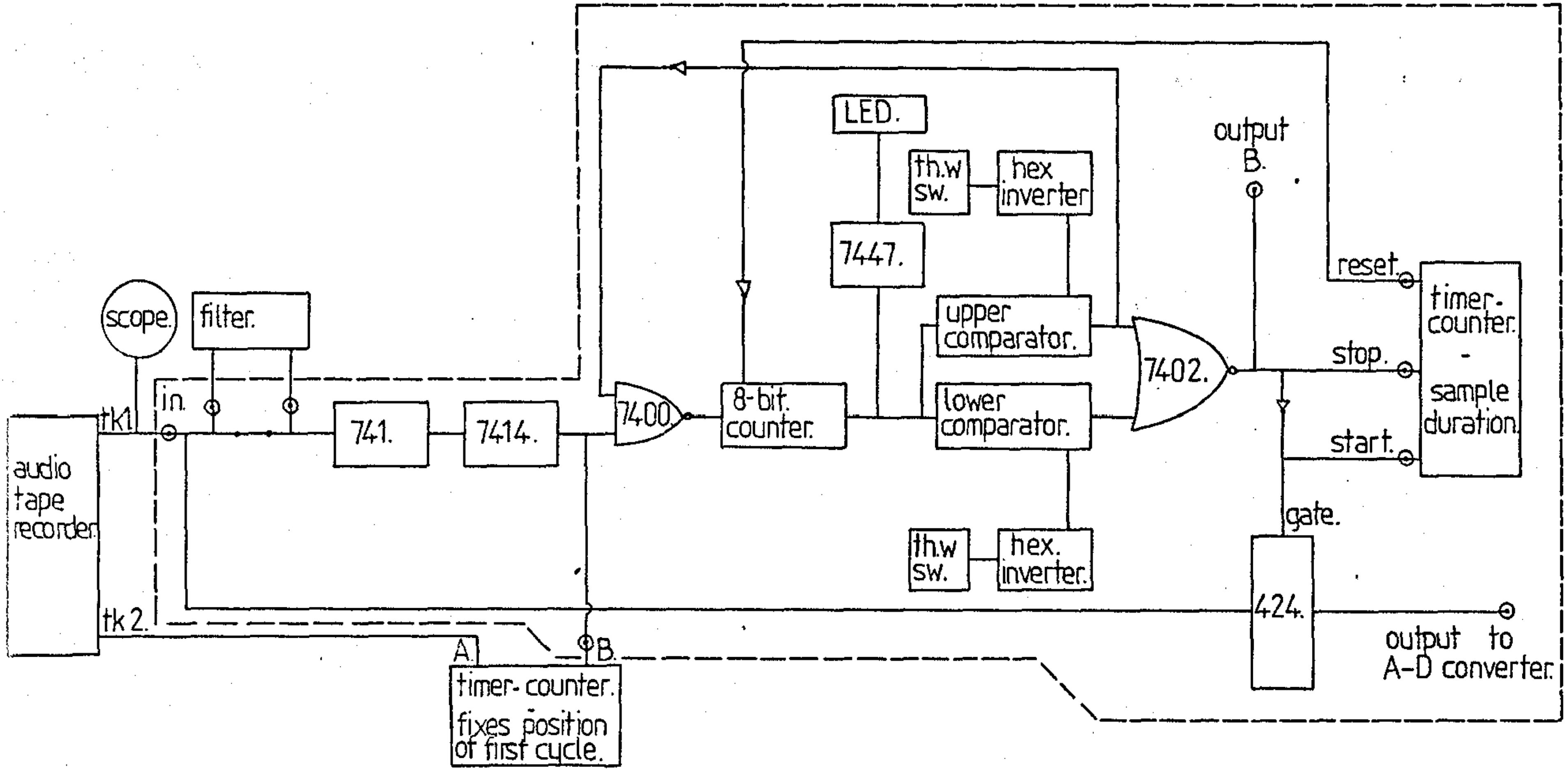

Fig. B2. Schematic Diagram of Sampling Device.

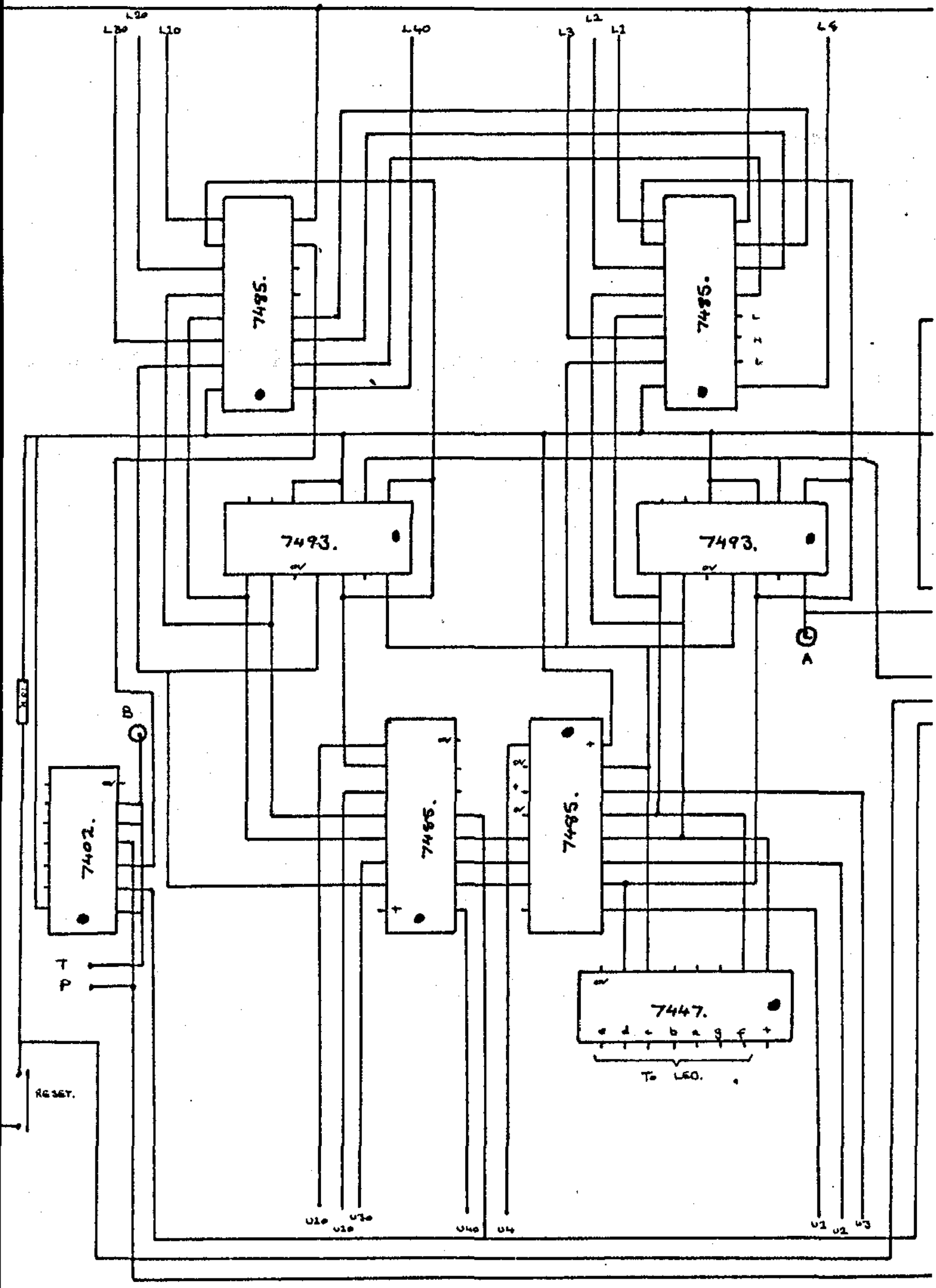

Fig. B3. Circuit Diagram of Sampling Device.

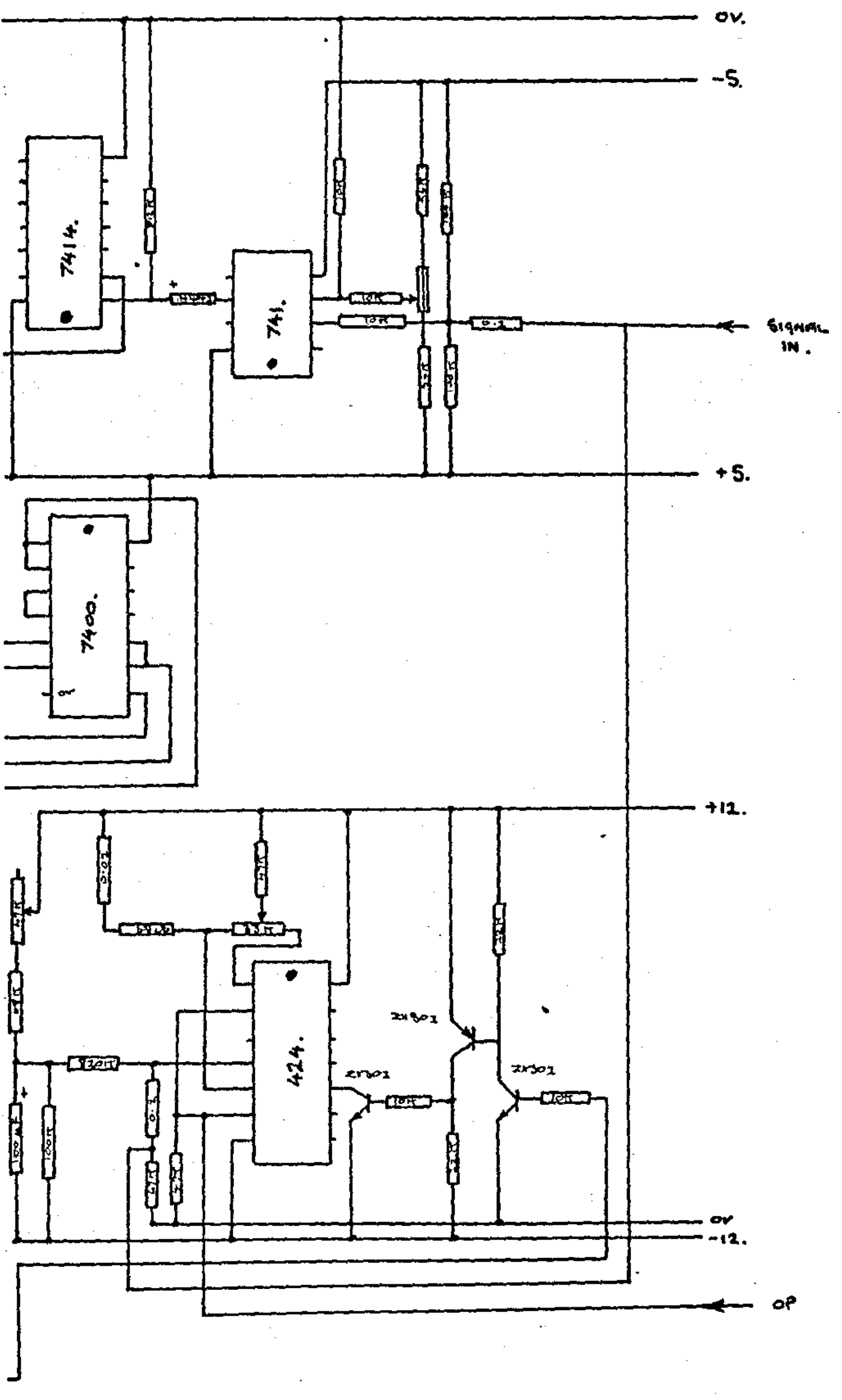
0V.
-5.
7414.
741.
10K
10K
0.1
SIGNAL IN.
+5.
7400.
+12.
0.01
424.
ZN301
ZN301
ZN301
10K
10K
100K
0.1
0V
-12.
OP

Fig. 23 part 2

a separate track. This signal will be called R, its beginning R_0 and end R_t. The end of the period is indicated by a pulse applied to input J on the counter taken from output A on the sampling device. This output, the first pulse of which begins the count on the 7493's, stops the timer-counter thereby defining the period from the moment at which the pallet valve was energised (a useful constant before which of course the pipe is unable to speak) and the first cycle which, in the case of a developing signal, reaches the voltage pre-set by the minimum voltage needed to produce an output from the op-amp. The period deduced by this will be shown on the results as the pre-onset time. Following this will be a period relating to the segment length before the first data sample point.

This same procedure is also used to define the duration of the decay transient. Its beginning is found by the end of the signal on the second track of the recorder. This marks the closing of the pallet valve. The end of the transient is found by the cessation of the signal from output A.

The Selection of Sampling Parameters

The sampling device enables a visual representation of onset transients to be built up by analysis of short segments of the recorded signals (ft) the duration of which (t_n) is related to the frequency of the signals' fundamental. Segments may contain any integer multiple of cycles of the fundamental. Analysis of the segments in terms of magnitude and phase for particular frequency components was possible using the 5451A Fourier Analysis system. Frequency changes occurring between successive samples could be traced using this device by comparing the frequency channels of the strongest components with the channels in which associated harmonics occur in preceeding and subsequent sample analysis. Therefore, the H.P. system is a tool capable of yielding the data required. However, the accuracy of phase and magnitude information is related to the accuracy of frequency data and also of course computer time available and data storage requirements. The choice of analysis parameters involves careful consideration since the system produces more rigorous results in one area only at the expense of accuracy in another.

Together the sample record length set on the A-D converter controls and the data block size N fix the number of data points in the frequency domain output, the maximum frequency analysed and the sampling of the signal presented for analysis. Clearly, the sample record length (T) must be longer than the sample duration (t_n). The segment length is dependent upon the frequency of the signal, the number of points required on the final graphs and the duration of the onset before a steady state is reached. This latter is determined from oscilloscope photographs of the onset triggered by signal R_0 from the second track of the tape. The photographs show clearly the length of the attack part of the transient. The number of cycles involved in this divided by the number of points required on the graphs determine the number of consecutive cycles which will form a sample.

Analysis of single cycles would produce more rigorous information than taking two or three cycles, but the volume of data produced and amount of computer time this would involve, make it necessary to determine segments made up of several cycles. Some tests were carried out in which early segments contained fewer cycles than later ones, giving greater accuracy to the part of the signal where most rapid changes were occurring. The results of R&D$_1$ and R&D$_2$ use this method but it was decided, because results so presented inherently give the impression of increased steadiness as the sound evolves and also because of the sampling error associated with short duration samples, to abandon this method in favour of segments of equal duration.

The sample duration time also effects the frequency resolution (Δf) of the frequency domain data. This is the number of Hz between successive frequency points. Components of frequencies other than those represented will not be shown in the output data.

thus: $T > t_n$

and $\frac{1}{T} = \Delta f$.

It is apparent therefore, that a greater degree of frequency resolution is given by selecting fewer sample points since this will enable T to be large and made Δf small. However, the sample interval (Δt) is effected both by T and the block size N, thus:

$$\Delta t = \frac{T}{N}$$

Therefore, if T is large and the sample presented is short, although the frequency domain information will be rich in frequency data, the analysis itself will be based on a poor sampling of the signal and the data produced may therefore be less rigorous.

The block size N, apart from its place as already shown in determining Δt, is chosen to enable the resolution of the highest frequency component required to figure in the results. The maximum frequency for resolution was decided by steady state analysis of the signals using the Ubiquitous Real-Time analyser. The results show the number of harmonics important in characterising the sound. These are monitored during the onset transients. The graphs also enable the highest frequency needed in the results to be calculated (f_n). The block size is determined thus:

Since $N = \frac{2 F_{max}}{f}$

$$N > \frac{2 f_n}{f}$$

Clearly, the choice of a high frequency maximum will necessitate the choice of a larger block size and will produce correspondingly more data-points per cycle. (number of datapoints = $\frac{N}{2}$).

To clarify the method of choosing parameters those adopted for pipes 3 will be discussed. From the 'scope pictures the total transient duration was approximately 50ms. 24 segments were therefore presented, each containing two cycles of the signal. The choice of sample lengths and total sample time for this analysis was determined only after several trial runs using different settings. The principal factors involved are frequency resolution, sampling and the time taken for the results to be printed. (see also later section on averaging) Initial runs using Δf of 5 or 10 Hz proved grossly unsatisfactory since the sampling per cycle was very poor. Using T = 50ms, 20 Hz resolution is achieved with a sampling of 4 per cycle of the signal. This too is poor. A further drawback is the large volume of data and the time involved in printing it. This is because many channels must be printed to ascertain the frequency changes. Combined with the averaging (see later) which increases the print out, this forced the 20 Hz Δf to be rejected. It was finally decided that the 20ms setting, with which Δf becomes 50 Hz and $\Delta t = \frac{0.02}{N}$, was the best compromise.

The choice of the value for N began with the examination of the real-time analyser plot. It shows the presence of 7 harmonics in the steady-state spectrum of pipe 3. However, preliminary analysis of the onset of 3 1.1 showed that harmonics 6 and 7 were so very constant that it would be more expedient to improve the frequency resolution and accept more data than to resolve these harmonics. The frequency f_n was therefore 900 Hz x 5 = 4500 Hz

Since $N > \frac{2 f_n}{f}$

for $T = 20\text{ms}$ $\therefore$ $\Delta f = 50$ Hz

then $N > 180$

since N must be apower of 2,

N is to be not less than 256.

Inserting this value of N to find Δt and multiplying this to find the number of times the signal is sampled it is found to be 28 times. However, increasing N to 512 increases this to 56 times. The higher rate is preferred therefore for analysis 3, taking two cycles per sample, the block size is 512 and the total time is 20ms. Analysis parameters for all the signals considered are shown in table 31.

Problems of instability and repeatability of musical sounds

Calibration of Sampling Device and Averaging

Initial tests of the method using signal generators proved entirely satisfactory and by setting the offset on the op amp of the sampling device to zero, results were obtained from signals of large and

Signal	A	B	C	R&D
Frequency	2,900 Hz	900 Hz	194 Hz	526 Hz
Onset Duration	20 ms	50 ms	170 ms	50 ms
No. of Harmonics	4	5	3	5
Fn	11,600 Hz	4,500 Hz	570 Hz	2,630 Hz
T	10 ms	10 ms	50 ms	20 ms
Δ f	100 Hz	100 Hz	20 Hz	50 Hz
N	256	128	64	128
F max	12,800 Hz	6,400 Hz	1,600 Hz	3,200
No. of cycles in onset	58	45	33	48
No. cycles/segment	2	2	2	3
No. points on graph	30	25	25	20
tn	0.6896 ms	2.222 ms	10.31 ms	5.703 ms

TABLE B 1 – ANALYSIS PARAMETERS – PIPES A, B, C, and R&D

small voltages. Subsequently, tests involving the recorded onsets from pipes R&D$_1$ and R&D$_2$ were carried out. For these the threshold was raised slightly above the level at which the background noise on the tape triggered the sampling device. Despite this, the method proved unsatisfactory as dissimilarities were found between the analysis of the same signals. The problem emerged in the analysis of R&D$_2$ and closer examination of the transient by making time domain graphs of the signals reveals a lack of similarity between subsequent onsets of the same pipe. This is illustrated in figure B4. Clearly the problems with the sampling device were due to the gate being opened by an early pulse large enough to trigger the device. Once open many smaller amplitude cycles passed through before the counters registered the final pulse and effected the closing of the gate.

The level at which the sampling device triggers must therefore be raised to trigger on the earliest regular impulse. This can be monitored from output A on the sampling device. Of interest too, due to the unsimilarity of repetitions, is the real-time position of the first pulse. This is therefore measuredusing a timer-counter started by the pulse R_o , which also triggers the storage 'scope the traces of which register the sampling device outputA and the signal output from the device. The first pulse from A inhibits the timer. The equipment is set up as shown in Fig. B 5.1 . The sampling device is set to allow only the first pulse through (setting 01 - 01) and, together with the timer-counter and the 'scope, it is reset. The tape is run and a trace appears on the 'scope. An incorrect sample produces the trace shown in Fig. B 5.2 . An early pulse has triggered the counters. The multiturn pot is adjusted from the position which produced this situation until a continuous signal is produced on the upper trace and the signal on the second trace is triggered by the first cycle of this continuous signal as shown in Fig. B 5.3 .

To assure that this condition is correct several repetitions are made. Once set, the eight recordings of the signal are examined similarly and further adjustment made if necessary until three signals can be chosen which fulfil the conditions of diagram 2 and show similar durations on the timer counter indicating that the amplitude of the first signals to be examined in all three cases are not only similar in level but also happen at a similar time. The isolation of three similar signals is important since averaging of segments which are out of step with each other could lead to distorted or inconclusive results.

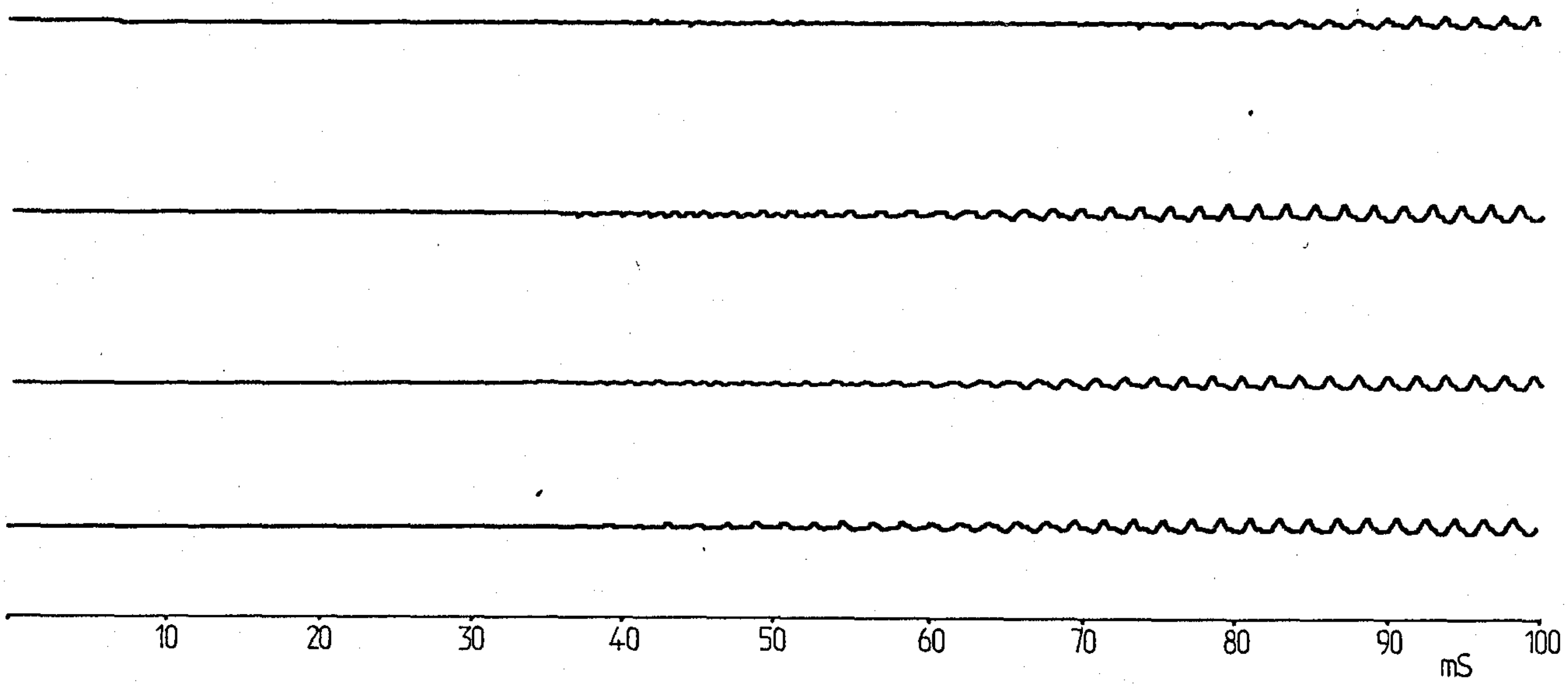

Fig. B4. Four Consecutive Onsets of Signal $R+D_2$

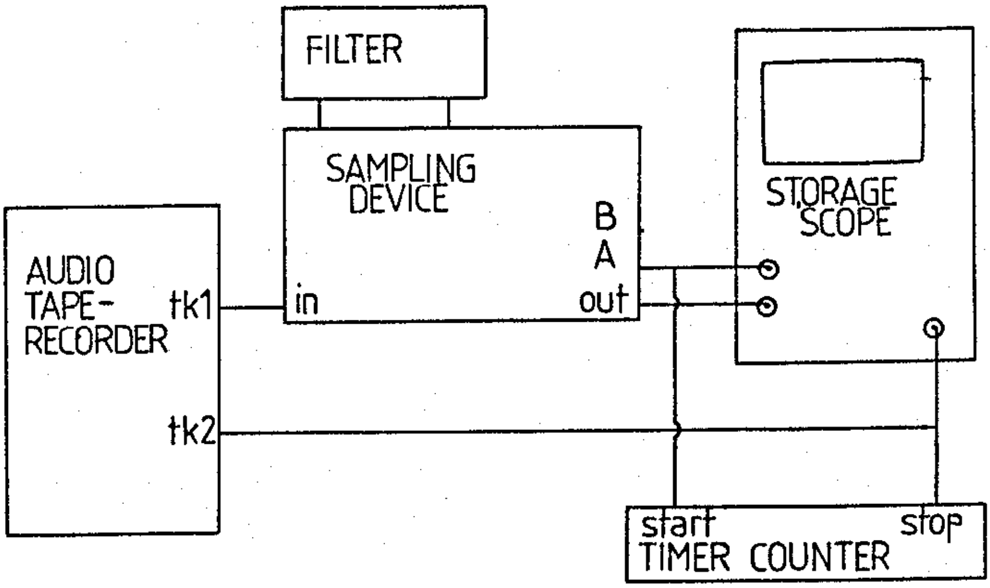

Fig. B 5.1 SETTING LEVEL FOR FIRST CYCLE

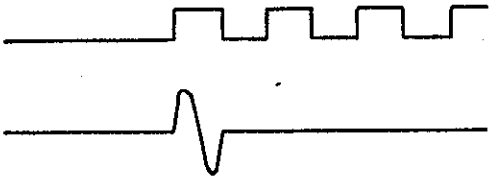

Fig. B 5.2 CORRECT LEVEL

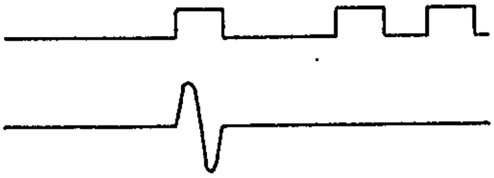

Fig. B 5.3 ERRONEOUS LEVEL

It is understood that omitting to examine samples with more divergent onsets is to ignore possible information about the variety found in the onset of a particular musical instrument, but since it is the object of this work to describe the characteristics of a sound's onset, it is reasonable to deal with those signals which constitute a norm, that they may be compared with others in order that conclusions can be drawn about their diversity.

Graphs finally produced are to show an average value for the magnitude of components and their frequencies. However, because of the nature of the presentation of data from the system, due to frequency information being gleaned from the channel number in which peak amplitudes are found, results can not be averaged for two reasons. Firstly, averaging of magnitude data would also necessitate averaging of phase information making the latter meaningless, and secondly, blocks are averaged channel by channel. Thus, if peak magnitudes occurred in different channels due to frequency fluctuations they would not be averaged together but with the values occurring in the related channels of other blocks. Therefore, initially the information must be presented for each analysed sound. For this reason, the time factor, averaging has been taken over the minimum three samples.

Processing of Results

Peak magnitude and associated frequency values in the form of channel numbers, were transferred to the Prime 1900 system whose Calcomp drawing facilities were used to produce graphs. The magnitude graphs, involving averaged data from the three samples of each segment, show each harmonic.

Validity of Analysis Method

The analysis of musical sounds having the form

$$f(t) = \sum_{i=1}^{\infty} D_i\,(t).\ \mathrm{Cos}\left[i\omega_i\ t+\theta i\right]$$

by the periodic Fourier function

$$f(t) = \sum_{i=1}^{N} D_i\left[(n-\tfrac{1}{2})T\right]\ .\ \mathrm{Cos}\left[i\omega_i\ \ t+\theta i\right]$$

w Will tend to produce certain inaccuracies dependent on the periodicity of the signal. The usefulness of segmental analysis of the type described is therefore dependent on the limitations imposed by the analysis of a quasi-periodic signal using the Fourier series for a periodic wave. The degree of error produced by this and also by two other factors, the determination of the beginning and end of the periods and numerical intergration, are important aspects of this form of analysis which must be taken into consideration when reviewing results and also, since the extent of inaccuracy is found to be minimal, validiate this as an acceptable analysis method. Examination of the implications of these errors is well documented.[1] A brief resume of the findings follows with reference to the mthod and equipment used in these experiments.

Several sources of discrepancy are inherent in the assumption that signals of the type under consideration can be approximated by a periodic function. An amplitude change in the component being evaluated or in the relative amplitudes of other components, for example, and also changes in the period length due to frequency perturbations may all lead to incorrect computation of magnitudes. However, the error produced by this is found to be significant only in the early periods of very short onset transients, otherwise it is undetectable by humans - less than 1 per cent in real terms. The level of inaccuracy caused by changing amplitudes depends on the relative changes between two components. This amounts to about 1 dB for lower components, and about 2 dB for others.

Fallacious data may be computed if the period being analysed does not exactly incorporate whole cycles of the signals' fundamental. This tends to arise since the intervals between successive positive-going zero crossings need not be the same as the period of the fundamental component, but significant errors will occur only when consecutive high order harmonics differ widely in amplitude at the same time as large errors in period determination occur. For this reason the duration of the segment is computed (Tc). Samples are rejected if $T_c - \Theta$ is not within a 2 per cent tolerance. By so doing, although some data may be lost, that which is produced should lie within a 3 per cent margin of error.

It is prudent to mention the errors which could occur in the computing system which are mainly related to the sampling rate. Faster sampling rates improve accuracy but increase computing time and storage requirements. Sampling errors are reduced by the factors inherent in the system used based on Shannon's sampling theorem: in order to completely recover a continuous signal from a sampled signal it is necessary that the repetition frequency of the sampling wave is such that at least two samples are taken of the highest significant frequency of the signal.

i.e. $F_{max} < \frac{1}{2\Delta t}$

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[1] Keeler (60)

However, since $\Delta f = F\ \mathrm{max}\ /N2 = (1/2\Delta t)/(N/2) = 1/N\Delta t = 1/T$. sampling errors will not occur in the digitalisation of the signal. Quantization error will occur but will not effect the data seriously.

The precision with which musical signals can be described using this method of analysis is shown by the small errors encountered. Keeler defines the limitations of the system, stating that accurate results can in general be produced for all components of waveforms whose transient portion is at least 12 periods long. Care is required however when dealing with adjacent components that differ greatly in amplitude.