Effects of infrasound on man

A monograph of research carried out at Aalborg University

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Preface

This monograph presents investigations and experiments carried out at Institute of Electronic Systems, in the period 1976-83. The manuscript has been submitted to the Faculty of Technology and Science at Aalborg University for the degree of Licentiatus, the Danish Ph. D. degree.

The book consists of 4 articles that were originally prepared for publication in the Journal of Low Frequency Noise and Vibration. One of them has already appeared in the Journal and the remaining three are at present under referee for publication. In addition to the four papers a brief summary is given in English and Danish.

The four papers have been chosen to give the best description of the research on infrasound carried out at Institute of Electronic Systems. During the project period a number of conference papers and reports have been prepared. A list of these is also included, together with a total list of literature on infrasound that has been read and thus has contributed to the selection of items for our work.

I am indebted to a number of people who have contributed to this project, either directly working on it or indirectly through their advice and encouragement.

Svend Lauritsen and Sven Hvid Nielsen worked on the design of the hydraulic infrasound generator. Unfortunately this generator failed to fulfill the strong demands made with respect to low levels of audio frequency sound and vibrations. However, the cooperation gave me a good insight into hydraulics and gave me an opportunity to use acoustical and electrical models when considering dynamic properties of hydraulic systems, a powerful technique that is not very widely known among hydraulicians. Gunnar Langkilde from The Laboratory of Heating and Air Conditioning at The Technical University of Denmark, lent us his equipment for measuring task performance and he also made some preliminary data analysis. Anders Bundgård Mortensen and Bjarne Kirk whom at the time were students at the Institute, took part in the study on physiological and task performance effects. Bjarne kept his association with the Institute when he participated in the work on equal loudness curves. Bruce Reid, Howard Community College, Columbia, Maryland, and Jente Andresen also took part in this aspect of the work at various times. My cooperation with Jente continued in the study on equal annoyance curves, where she - being a psychologist - contributed invaluably to further development of the rating technique. Steffen Lauritzen and Aage Nielsen have acted as statistical consultants and Ole Jordan, Audiology Department, Aalborg Main Hospital, has frequently been consulted in medical questions. Throughout the project period I have discussed the results and plans for future work with Jørgen Bach Andersen and Per Rubak, the former being official supervisor for my first 3 year scholarship period.

Invaluable inspiration has also been obtained from international cooperation which has included participation in conferences, visits to other laboratories, organization of the Conference on Low Frequency Noise and Hearing at our Institute in 1980 and membership of the Editorial Board of Journal of Low Frequency Noise and Vibration. I would like to mention the especially fruitful encouragement I have had from discussions with H.G. Leventhall, Atkins Research and Development, formerly Chelsea College, London University.

This project has been supported by grants from the Siemens Foundation, Rockwool Acoustics Research Committee, Danish Council for Scientific and Industrial Research, Directorate-General of Social Affairs and Directorate-General for Research, Science and Education, Commission of the European Communities, and from several sources within Aalborg University. I wish to express my sincere thanks for this support.

Aalborg, 13 April 1984.

Henrik Møller.

The defense of this work took place on May 25. 1984. October 10. 1984 Henrik Møller was awarded the Danish Ph. D. degree, lic. techn.

Aalborg, October 15. 1984.

Jørgen Østergaard

Dean

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Summary

Introduction

In the middle of the nineteen seventies when this research was initiated, a number of papers in periodicals and at conferences had proposed the existence of extra-auditory effects of infrasound. It was widespread opinion that infrasound might cause disturbances of human body functions and influence the performance of humans. Often mentioned effects were changes in blood pressure, heart rate and respiration, disturbance of equilibrium, changes in production of stress-hormones and secretion of gastric juice, increase of reaction time and deterioration of performance in vigilance tasks.

The subject was also taken up by the daily press and severe and mysterious effects of the "inaudible" infrasound were reported. The fact that infrasound above a certain limit is audible was hardly mentioned although a threshold curve for infrasonic frequencies had been described by Georg von Békésy as early as 1936.

Many resources were spent on measurement of infrasound and unexpectedly high levels were detected in industry and transportation. Some infrasound was also found in office buildings and in private homes where the main sources were ventilating plants, nearby industry and traffic. The widespread use of the A-filter in noise measurements had left these low frequencies undiscovered.

The experimental evidence of the effects of infrasound was, however, rather sparse. Only few studies had been carried out and the results of these were not concordant. The research involved laboratory experiments and field studies. The main advantages of field studies are the possibilities of having a large number of people involved and of using long exposure times. Field studies may be the only possible way of finding long term effects. However, it is a very severe disadvantage that the characteristics of the exposure are less known than in laboratory experiments. This is especially a problem with infrasound since in a real world environment, infrasound is usually found together with other environmental factors, for example audio frequency noise, vibrations, heat and chemical factors. Even in laboratory experiments it is very difficult to produce infrasound without vibrations and with a sufficiently low distortion.

We decided to build a test chamber where 2-3 subjects could be exposed to infrasound while their reactions could be monitored. Paper A describes this chamber, while the first experimental series, dealing with physiological and task performance effects, is covered by paper B. The conclusion of these experiments were that only few - if any - extra-auditory effects were seen from infrasound at moderate levels. However, the subjective annoyance from audible infrasound was very obvious, and this led to the investigations of loudness (paper C) and annoyance (paper D).

Test chamber (Paper A)

The chamber has a volume of 16 cubic metre and it is built of concrete. The infrasound generator was originally designed as an aluminium membrane covering a 2 square metre hole in one wall of the chamber. However, it turned out that the hydraulic system constructed to vibrate the membrane was not able to produce an oscillation sufficiently free from harmonic distortion to keep sound in the audio range below threshold.

Therefore, the existing system with 16 electrodynamic loudspeakers was designed. The frequency range is 0.05 - 30 Hz, covering the most important part of the infrasonic range and giving an overlap into the audio range. The system does not utilize any acoustical resonances, thus giving a flat frequency response. In this way it is possible to reproduce a real environmental signal recorded on tape.

The maximum obtainable sound pressure level - 125 dB rms - is sufficient to cover most of the usually occurring environmental infrasound. If higher levels are needed, the 5 cubic metre chamber enclosing the back of the loudspeakers can be used, as the sound pressure level is 10 dB higher here. Unwanted effects from the infrasound generator such as vibrations, harmonic distortion and audio frequency noise have been kept so low that they are not expected to influence the experiments. For experiments of longer duration, the room is equipped with a ventilating system, which gives sufficient air exchange for 3 persons. When in use this system increases the lower limiting frequency to 0.3 Hz.

Physiological effects and effects on task performance (Paper B)

In these experiments 16 subjects (healthy students with normal hearing) were each exposed to the four sound conditions: 6-30 Hz noise below the hearing threshold, 6-30 Hz noise slightly above the hearing threshold, a silent control condition and - for comparative reasons - traffic noise at an equivalent continous sound level of 71 dB(A).

During the experiments the subjects worked on various tasks from which the speed and accuracy were observed. Also recordings were made on blood pressure, heart rate and hearing before and after each experiment.

Neither the audible nor the inaudible infrasound caused any changes in the cardiovascular or hearing parameters. Only one of 17 task performance parameters showed a deterioration during exposure to audible infrasound.

After each experiment the subjects filled out a questionnaire concerning their experiences during the noise exposure. From the audible infrasound high ratings of annoyance were obtained and the subjects indicated a feeling of pressure on the ears.

These findings suggested that extra-auditory effects had been exaggerated in the literature, while effects related to the hearing had been underestimated. Therefore, a better knowledge was required about the hearing function at infrasonic frequencies. In particular, the fact that infrasound less than 20 dB above the hearing threshold was rated close to "very annoying" emphasized the need for a better knowledge about the growth of loudness and annoyance above threshold. This led to the two studies of loudness (paper C) and annoyance (paper D).

Loudness (Paper C)

Points of equal loudness were determined through direct comparisons of two tones, each having a duration of 2 seconds. The subjects were 20 normal hearing students aged between 18 and 25, and the psychometric method was based on maximum-likelihood estimation of psychometric functions. Contours of equal loudness were determined in the frequency range 2-63 Hz and the loudness range 20-100 phon. The loudness curves run almost parallel in the infrasound region, and much closer than in the audio region. For example, the distance between the 20 and the 80 phon curves has decreased from 60 dB at 1000 Hz to approximately 16 dB at 8 Hz. Consequently, infrasound only a few dB above the hearing threshold will seem loud. It is also possible to explain the fact known from the literature that a small change in the infrasound content of a complex sound may change the loudness of the sound considerably.

The contours complement very well existing knowledge about the hearing at infrasonic frequencies, although there are minor but statistically significant disagreements with the low-frequency part of the ISO/R 226 loudness curves.

For audiosound the agreement between annoyance and loudness is usally so good that dB(A) and similar measures developed from loudness investigations can be used as estimates of the annoyance effect. However, the close relation between annoyance and loudness found at higher frequencies may not exist in the infrasound region, because very low frequencies are perceived as a throbbing sound instead of a tone, and this may have an influence on the annoyance experience. Therefore an additional study on the annoyance of infrasound was carried out (paper D).

Annoyance (Paper D)

While the equal loudness curves were determined through direct comparisons of two short tones, a similar procedure was not possible when considering annoyance. It is wellknown that the assessment of annoyance may vary with exposure time and an exposure of 15 minutes was considered necessary to get reliable annoyance ratings.

Instead of making direct comparisons the subjects rated the annoyance of 18 sound stimuli on a graphic scale. The exposures were: four infrasonic and low audio frequencies at different intensity levels and four levels of a 1000 Hz octave-filtered pink noise for reference. Equal annoyance contours were constructed to connect points that caused the same annoyance rating.

The equal annoyance curves demonstrate the not very surprising fact that the lower the frequency the greater the sound pressure must be to cause a given amount of annoyance. Compared with 1000 Hz the curves lie much closer in the infrasonic range. This change is already seen in the low frequency region, but becomes even more pronounced with decreasing frequency.

The loudness and the annoyance curves are remarkably similar in their general shape, especially when one considers that they have been established by two very different methods and that the number of subjects used in the two studies is rather small. Thus the relation between loudness and annoyance found at higher frequencies seems to hold for the low and infrasonic regions too.

Conclusion

The above described research suggests that extra-auditory effects of infrasound have been exaggerated, while effects related to the hearing have been underestimated. Audible infrasound is considered annoying and the annoyance seems to be related to the loudness of the sound.

Curves of equal loudness and equal annoyance demonstrate that the lower the frequency the greater the sound pressure must be to cause a given amount of loudness or annoyance. At infrasonic frequencies, the curves lie much closer together than at say 1000 Hz. This implies that relatively small changes in sound pressure may cause large changes in the sensation. From an environmental point of view, this is important because a modest reduction in sound pressure will in some cases be enough to alleviate annoyance caused by infrasonic noise. It also means that accuracy is crucial when measuring infrasound and that specific demands must be made on the measuring equipment.

As the existing weighting curves such as the A-curve do not cover the infrasonic frequency region, they cannot, of course, be used for measurement of noise having a significant infrasonic content. Even an extension downward in frequency of one of the curves would not solve the problem. The fact that the annoyance and the loudness curves show a decreasing steepness in the low frequency region with increasing level implies that a number of curves with different relative weighting of medium, low and infrasonic frequencies would be necessary. It also explains that use of the A-curve - which is approximately the reciprocal of the 40 phon curve - leads to an underestimation of loudness and annoyance from noise sources with considerable low frequency energy.

As the slopes of the equal loudness and equal annoyance curves are reasonably independent of the sound pressure level within the infrasonic range, a single weighting curve for this frequency region (possibly covering a part of the lowest audio frequencies as well) would be a better solution.

The Technical Committee 43 of the International Standardization Organization is considering a proposal for a procedure to be used when measuring noise in the infrasonic range. The proposal comprises two weighting curves with different slopes, namely 6 dB per octave (N-weighting) and 12 dB per octave (P-weighting). The mean slopes found in our investigations were 12.3 dB per octave for the loudness curves (2-31.5 Hz) and 11.7 dB per octave for the annoyance curves (4-31.5 Hz). It is obvious that the curve with a slope of 12 dB per octave will give the best estimates of loudness and annoyance.

It should not be forgotten that this conclusion has been drawn from experiments that have been restricted in many ways; only students have been used as subjects, no exposures were longer than 3 hours, the exposures used when studying physiological effects and effects on task performance were somewhat below the maximum levels found in industry and transportation, the performance tests used were all relatively simple, the loudness and the annoyance curves were only determined for pure tones, no studies were made on effects of combinations of infrasonic and audio frequency noise etc. etc. The significance of some of these restrictions will be investigated in future studies.

Resumé (in Danish)

Introduktion

Da denne forskning blev påbegyndt i midten af 1970'erne, var det i en række tidsskriftsartikler og konferenceindlæg blevet hævdet, at infralyd kunne påvirke mennesket på forskellig vis. Det var en udbredt opfattelse, at infralyd kunne forstyrre kroppens funktioner og påvirke vore præstationer. Blandt de ofte nævnte virkninger var ændringer i blodtryk, hjertefrekvens og vejrtrækning, forstyrrelser af ligevægten, ændringer i produktion af stresshormoner og udskillelse af mavesyre, stigning i reaktionstiden og forringelse af præstationer i årvågenhedsopgaver.

Emnet blev også taget op af dagspressen og voldsomme og mystiske effekter af den "uhørlige" infralyd blev rapporteret. Det faktum, at infralyd over en bestemt grænse er hørbar, blev næppe nævnt, selvom Georg von Békésy havde beskrevet en tærskelværdikurve for infralyd så tidligt som i 1936.

Der blev sat mange ressourcer ind på målinger af infralyd, og man fandt uventet høje niveauer i industrien og i transportsektoren. Der blev også fundet infralyd i kontorbygninger og i private hjem, hvor hovedkilderne var ventilationssystemer, nærliggende industrivirksomheder og trafik. Den udbredte anvendelse af A-filtret ved støjmålinger havde medført, at disse lave frekvenser hidtil var blevet overset.

De videnskabelige beviser for infralydens effekter var imidlertid ret sparsomme. Der var kun udført få undersøgelser, og resultaterne af disse var ikke overensstemmende. Forskningen omfattede laboratorieeksperimenter og feltundersøgelser. De væsentligste fordele ved feltundersøgelser er, at mange mennesker kan deltage, og at der kan anvendes lange påvirkningstider. Feltundersøgelser kan være den eneste måde at finde langtidseffekter på. Det er imidlertid en alvorlig ulempe, at påvirkningen er mindre kendt end i laboratorieeksperimenter. Dette er specielt et problem med infralyd, idet infralyd i det virkelig liv som regel findes sammen med andre miljøfaktorer som for eksempel normal støj, vibrationer, varme og kemiske faktorer. Selv i laboratorieeksperimenter er det vanskeligt at producere infralyd uden vibrationer og med tilstrækkelig lav forvrængning.

Vi besluttede at bygge et rum, hvor 2-3 forsøgspersoner kunne udsættes for infralyd, medens deres reaktioner kunne iagttages. Artikel A giver en beskrivelse af dette rum. Artikel B beskriver den første forsøgsserie, som omhandlede fysiologiske effekter og indvirkning på arbejdsevnen. Konklusionen på disse eksperimenter var, at infralyd ved moderate niveauer kun havde ringe - hvis nogen overhovedet - indflydelse på mennesket, udover at den kunne høres. Imidlertid var den subjektive gene fra den hørbare infralyd tydelig, og dette førte til undersøgelserne af hørestyrke (artikel C) og genevirkning (artikel D).

Infralydrum (Artikel A)

Rummet er bygget af beton, og det har et rumfang på 16 kubikmeter. Det var oprindelig meningen, at infralyden skulle genereres af en 2 kvadratmeter stor aluminiummembran anbragt i et hul i den ene væg. Det viste sig dog, at det hydrauliske system, som skulle bevæge membranen, ikke var i stand til at producere en bevægelse, som var tilstrækkeligt fri for harmonisk forvrængning til at holde lyden i audioområdet under tærskelværdien.

Det eksisterende system med 16 elektrodynamiske højttalere blev derfor konstrueret. Frekvensområdet er 0,05-30 Hz, hvilket dækker den vigtigste del af infralydområdet samt den laveste del af audioområdet. Systemet har en flad frekvensgang, idet det ikke udnytter nogen akustisk resonans. På denne måde er det muligt at gengive et signal fra det virkelige liv optaget på bånd.

Det maksimalt opnåelige lydtrykniveau - 125 dB rms - er så højt, at de fleste virkeligt forekommende infralydniveauer kan gengives. Hvis det er nødvendigt med højere niveauer, kan det 5 kubikmeter store rum, som dækker bagsiden af højttalerne bruges, idet lydtrykket her er cirka 10 dB højere. Uønskede effekter fra infralydgeneratoren såsom vibrationer, harmonisk forvrængning og støj i audioområdet er holdt på så lave niveauer, at de ikke forventes at påvirke eksperimenterne. Af hensyn til eksperimenter af længere varighed er rummet udstyret med et ventilationssystem, som giver tilstrækkeligt luftskifte til 3 personer. Når dette system bruges, stiger rummets nedre grænsefrekvens til 0,3 Hz.

Fysiologiske effekter og indvirkning på arbejdsevnen (Artikel B)

I disse eksperimenter blev 16 forsøgspersoner (sunde studenter med normal hørelse) hver udsat for 4 lydbetingelser: 6-30 Hz støj under høretærsklen, 6-30 Hz støj lige over høretærsklen, en kontrolbetingelse uden støj og - af hensyn til sammenligninger - trafikstøj ved et ækvivalent kontinuert lydniveau på 71 dB(A).

Under eksperimenterne arbejdede forsøgspersonerne på forskellige opgaver, fra hvilke hastighed og nøjagtighed blev registreret. Der blev også målt blodtryk, puls og hørelse før og efter eksperimenterne.

Hverken den hørbare eller den ikke hørbare infralyd gav nogen ændring i kredsløbsparametrene eller hørelsen. Kun en ud af 17 arbejdsevneparametre blev forringet under påvirkning af den hørbare infralyd.

Efter hvert forsøg udfyldte forsøgspersonerne et spørgeskema vedrørende deres oplevelser under støjpåvirkningen. Efter den hørbare infralyd angav forsøgspersonerne en høj grad af gene, og de angav at have følt en trykken for ørerne. Disse resultater pegede på, at de ekstraauditive effekter var blevet overdrevet i litteraturen, medens effekter knyttet til hørelsen var blevet undervurderet. Det var derfor nødvendigt med et bedre kendskab til hørelsen ved infralydfrekvenserne. Det faktum, at infralyd mindre end 20 dB over høretærsklen fik en vurdering tæt ved "meget generende" understregede behovet for et bedre kendskab til stigningen af hørestyrke og genevirkning over tærskelværdien. Dette førte til de to undersøgelser af hørestyrke (artikel C) og genevirkning (artikel D).

Hørestyrke (Artikel C)

Punkter med samme hørestyrke blev bestemt gennem direkte sammenligninger af to toner, som hver havde en varighed af to sekunder. Forsøgspersonerne var 20 normalthørende studenter mellem 18 og 25 år, og den psykometriske metode var baseret på maximum-likelihood estimering af psykometriske funktioner. Kurver for samme hørestyrke blev bestemt i frekvensområdet 2-63 Hz og hørestyrkeområdet 20-100 phon. Hørestyrkekurverne løber næsten parallelt i infralydområdet og meget tættere end i audioområdet. Eksempelvis er afstanden mellem 20 og 80 phon kurverne faldet fra 60 dB ved 1000 Hz til ca. 16 dB ved 8 Hz. Infralyd få dB over høretærsklen vil derfor synes kraftig. Det er også muligt at forklare det fra litteraturen kendte fænomen, at en lille ændring i infralydindholdet af en kompleks lyd kan ændre hørestyrken af lyden betragteligt.

Kurverne passer fint sammen med vort eksisterende kendskab til hørelsen ved infralydfrekvenser. Der er dog mindre men statistisk signifikante afvigelser fra lavfrekvensdelen af ISO/R 226 hørestyrkekurverne.

For normal støj er overensstemmelsen mellem genevirkning og hørestyrke som regel så god, at dB(A) og tilsvarende mål udviklet fra hørestyrkeundersøgelser kan bruges som estimater for genevirkningen. Den tætte sammenhæng mellem genevirkning og hørestyrke, som findes ved højere frekvenser, behøver dog ikke eksistere i infralydområdet, idet meget lave frekvenser opfattes som en pulserende lyd i stedet for en tone, og dette kan have indflydelse på geneopfattelsen. Der blev derfor foretaget en særlig undersøgelse af genevirkningen af infralyd (artikel D).

Genevirkning (Artikel D)

Medens hørestyrkekurverne kunne bestemmes gennem direkte sammenligninger af to korte toner, er det ikke muligt at anvende en tilsvarende procedure, når det drejer sig om genevirkning. Det er velkendt at vurderingen af gene kan variere med påvirkningstiden, og det blev vurderet, at en påvirkningstid på 15 minutter var nødvendig for at få pålidelige genevurderinger.

I stedet for at lave direkte sammenligninger vurderede forsøgspersonerne genen fra 18 lydpåvirkninger på en grafisk skala. Påvirkningerne var: 4 infralydfrekvenser ved forskellige intensitetniveauer og 4 niveauer af en 1000 Hz oktavfiltreret lyserød støj. Kurver for samme genevirkning blev konstrueret, således at de forbandt punkter, som gav samme genevurdering.

Kurverne demonstrerer det ikke overraskende faktum, at jo lavere frekvensen er, jo større må lydtrykket være for at give anledning til en bestemt grad af gene. Sammenlignet med 1000 Hz ligger kurverne meget tættere i infralydområdet. Denne ændring ses allerede i lavfrekvensområdet, men den bliver stadig mere udtalt med faldende frekvens.

Hørestyrke- og genevirkningskurverne er bemærkelsesværdigt ens i deres facon, specielt når man tager i betragtning, at de er blevet bestemt ved to meget forskellige metoder, og at antallet af forsøgspersoner i de to undersøgelser er forholdsvis lille. Den sammenhæng som ved højere frekvenser er fundet mellem hørestyrke og genevirkning ser derfor ud til også at gælde for lavfrekvens- og infralydområdet.

Konklusion

Den ovenfor beskrevne forskning tyder på, at de ekstraauditive effekter af infralyd er blevet overdrevet, medens effekter med relation til hørelsen er blevet undervurderet. Hørbar infralyd vurderes som generende, og genen synes at være sammenhængende med hørestyrken af lyden.

Kurver for samme hørestyrke og samme genevirkning viser, at jo lavere frekvensen er, jo større må lydtrykket være for at forårsage en given hørestyrke eller genevirkning. Kurverne ligger meget tættere sammen ved infralydfrekvenser end ved for eksempel 1000 Hz. Det medfører, at relativt små ændringer i lydtrykket kan give store ændringer i opfattelsen. Dette er af stor betydning i miljøsammenhænge, idet en beskeden reduktion i lydtrykket i nogle tilfælde vil være tilstrækkelig til at fjerne genen fra infralyd. Det betyder også, at nøjagtigheden er afgørende, når man måler infralyd, og at der må stilles helt specielle krav til måleudstyret.

Eftersom de eksisterende vægtningskurver som for eksempel A-kurven ikke dækker infralydområdet, kan de naturligvis ikke bruges til måling af støj, som har et væsentligt infralydindhold. Det vil ikke engang løse problemet, at forlænge en af kurverne nedad i frekvens. Fordi genevirknings- og hørestyrkekurverne viser en faldende hældning i lavfrekvensområdet med stigende niveau, vil det være nødvendigt med adskillige kurver med forskellig relativ vægtning af middel-, lav- og infralydfrekvenser. Dette forklarer også, at brugen af A-kurven - som tilnærmet er det reciprokke af 40 phon kurven - fører til en undervurdering af hørestyrke og gene fra støjkilder med betydelig energi i det lave audioområde.

Eftersom hældningen af hørestyrke- og genevirkningskurverne er nogenlunde uafhængig af lydtrykniveauet indenfor infralydområdet, vil det være en bedre løsning med en enkelt vægtningskurve for dette frekvensområde (eventuelt inklusive den laveste del af audioområdet).

Et forslag til målemetode for infralyd er netop under behandling i Technical Committee 43 under International Standardization Organization. Forslaget omfatter to vægtningskurver med forskellig hældning, nemlig 6 dB per oktav (N-vægtning) og 12 dB per oktav (P-vægtning). I vores undersøgelser fandt vi middelhældninger på 12,3 dB per oktav for hørestyrkekurverne (2-31,5 Hz) og 11,7 dB per oktav for genevirkningskurverne (4-31,5 Hz). Det er klart, at kurven med en hældning på 12 dB per oktav vil give de bedste estimater af hørestyrke og genevirkning.

Det må ikke glemmes, at denne konklusion er draget udfra eksperimenter, som har været begrænset på mange punkter; som forsøgspersoner blev anvendt studenter, ingen påvirkning var længere end 3 timer, de påvirkninger, som blev anvendt i undersøgelsen af fysiologiske effekter og indvirkning på arbejdsevnen var noget under de maksimale niveauer, som findes i industrien og i transportsektoren, arbejdsevnemålingerne blev foretaget med relativt simple opgaver, hørestyrke- og genevirkningskurverne blev kun bestemt for rene toner, der blev slet ikke udført undersøgelser af effekter af kombinationer af infralyd og normal støj o.s.v., o.s.v. Betydningen af nogle af disse begrænsninger vil være emnet for fremtidige undersøgelser.

Original papers

Paper A: Construction of a test chamber for human infrasound exposure. *(Henrik Møller).*

Paper B: Physiological and psychological effects of infrasound on humans. *(Henrik Møller).*

Paper C: Loudness of pure tones at low and infrasonic frequencies. *(Henrik Møller and Jente Andresen).*

Paper D: Equal annoyance contours for infrasonic frequencies. *(Jente Andresen and Henrik Møller).*

Paper A

Construction of a test chamber for human infrasound exposure

Construction of a Test Chamber for Human Infrasound Exposure.

by Henrik Møller,
Institute of Electronic Systems, Aalborg University, Denmark.

Summary.

The report describes the construction of an infrasound test chamber, in which subjects can be exposed to controlled infrasound signals.

The infrasound is produced by 16 electrodynamic loudspeakers, mounted in one wall of the 16 m^3 chamber. The maximum sound pressure level that can be obtained is 125 dB rms in the frequency range 0.05 Hz - 30 Hz. At a level of 120 dB the 2nd and 3rd harmonic distortions are below 1%. The system does not utilize any acoustical resonances, thus giving a flat frequency response. In this way it is possible to reproduce a real environmental infrasound signal recorded on tape.

For the purpose of experiments of longer duration, the room is equipped with a ventilating system, which gives sufficient air exchange for 3 persons. When in use this system increases the lower limiting frequency to 0.3 Hz.

Introduction.

It has often been claimed that infrasound may influence the human being. The proposed effects are physiological effects such as changes in heart rate and blood pressure, effects on task performance, and a number of nuisances like dizziness, nausea, loss of concentration and headache. Therefore a number of investigations have been carried out involving both field studies and laboratory experiments.

The main advantages of field studies are the possibilities of having a large number of people involved and of using long exposure times. Field studies may be the only possible way of finding long term effects. However, it is a very severe disadvantage, that the characteristics of the exposure are less known than in laboratory experiments. Especially when considering infrasound this is a problem, since infrasound is usually found together with other environmental factors, for example audible noise, vibrations, heat and chemical factors. Even in laboratory experiments it is very difficult to produce infrasound without vibrations and with a sufficiently low distortion.

At Aalborg University it was decided to build a test chamber where subjects could be exposed to infrasound in the frequency range from below 1 Hz to 20 Hz. The dynamic range which were to be covered was that of everyday environmental infrasound, for example up to 120-130 dB. The infrasound should have a low harmonic distortion and be free from any noise in the audio frequency range. It would be preferable if the infrasound could be electronically controlled with a flat frequency response, so that not only pure tones could be reproduced but also noise bands and environmental infrasound recorded on tape. The vibration levels at the floor and the walls should be kept as low as possible. The chamber should be so large that two or three subjects can be under test at a time, and that the psychological influence of being in a "test chamber" can be ignored.

A chamber which fulfils these requirements to a reasonable extent has been built, and it has already shown its usefulness in a number of experiments. The first approach was a room with a 2 square metre aluminium membrane driven by a hydraulic system. It was able to produce sound pressure levels up to 135 dB. However, both the harmonic distortion and the vibration level at the floor were too high, and other solutions were considered.

The most obvious generator of infrasound with low distortion would be electrodynamic loudspeakers. A low vibration level could also be expected since the mass of the membranes is very low. The reason why loudspeakers were not used at first was that they are not made for use at so low frequencies, and consequently the maximum amplitude of the membrane stroke was expected to be too low. But after the hydraulic system had failed to give sufficient low distortion, a number of electrodynamic loudspeakers were tested concerning their properties at high amplitudes [1]. Two different loudspeakers showed to be equally good, as they were both able to move about 0.75 litre of air peak to peak. One was a 10 inch loudspeaker with an extremely long stroke, and the other was a more ordinary 13 inch. The smaller one was made especially to order, but as the bigger one was already in normal production, this one was chosen.

Description of the room.

Figure 1 shows the test chamber from above. Actually there are two rooms the loudspeakers operate between. The experiments are carried out in the biggest room, the test chamber, whereas the smaller one, the back volume, encapsulates the back side of the loudspeakers, so that the infrasound is not radiated from the system.

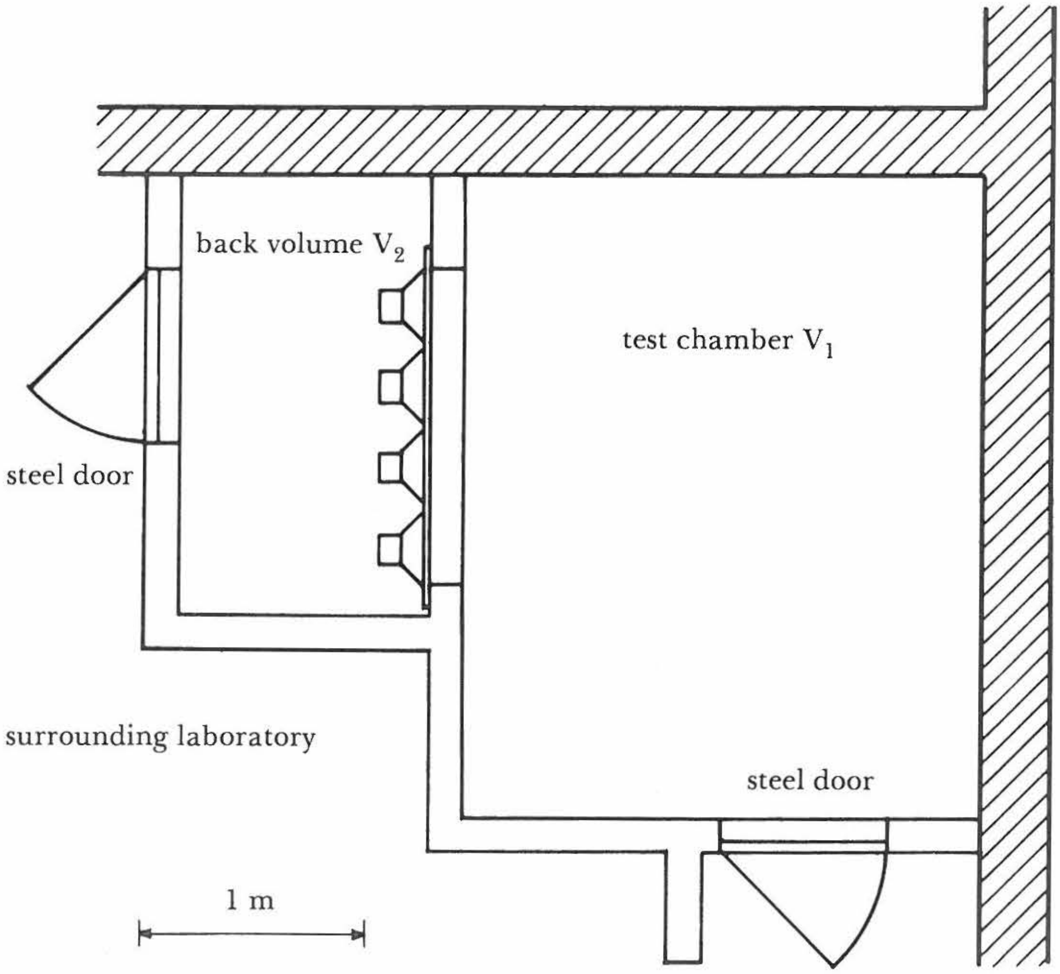

Figure 1. The infrasound laboratory seen from above.

The chamber is built of concrete in a corner of the laboratory. Concrete is chosen as it is stiff and heavy, so vibrations and bending of the walls are largely avoided. Unfortunately concrete is also very porous, and in order to keep the room reasonably tight, it has been necessary to cover all surfaces with a thick polyurethan paint. In spite of this there is a small leakage, and the room does not work down to DC.

The volume of the chamber is 15.8 cubic metre, and the largest dimension is 2.9 metre. The wavelength of a 20 Hz pure tone is 17 metre, so the room performs approximately as a pressure chamber in the infrasound range. The connexion between the instantaneous sound pressure $\Delta p(t)$, and the instantaneous volume displacement $\Delta V_1(t)$, is as follows:

$$\Delta p(t) = -\gamma p_0 \Delta V_1(t)/V_1$$

where γ is 1.4 because the process is adiabatic, p_0 is the atmospheric pressure (10^5 Pa), and V_1 the volume of the chamber.

16 loudspeakers are installed, and as the maximum obtainable volume displacement for one loudspeaker is 0.75 litre peak to peak, the maximum sound pressure level can be calculated to 106 Pa (134 dB) peak to peak, or for pure tones 38 Pa (125 dB) rms.

Generation of infrasound with electrodynamic loudspeakers.

When the 16 loudspeakers are mounted between the test chamber and the back volume, the equivalent diagram in figure 2 is valid. The electrical part consists of the voltage across the terminals u(t), current in the coil i(t), coil resistance R_e, and the feedback from the membrane movement Blv(t), where Bl is the magnetic field multiplied by the coil length, and v(t) the membrane velocity.

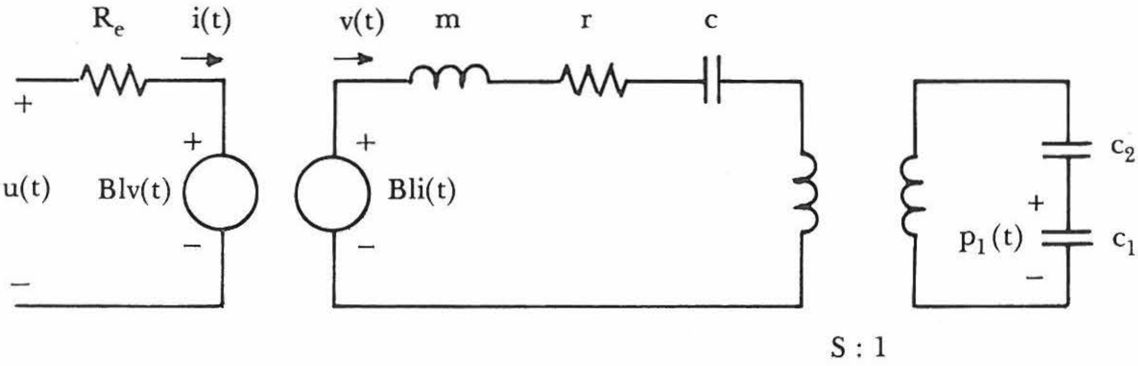

Figure 2. Equivalent diagram of infrasound generating system. $R_e = 5.6\Omega$, $Bl = 13.7$ N/A, $m = 0.078$ kg, $r = 1.8$ Ns/m, $c = 0.92 \cdot 10^{-3}$ m/N, $S = 0.053$ m^2, $c_1 = (V_1/16)/\gamma p_0 = 7.1 \cdot 10^{-6} m^5 N^{-1}$, $c_2 = (V_2/16)/\gamma p_0 = 2.3 \cdot 10^{-6} m^5 N^{-1}$.

The mechanical part includes the force from the electrical current Bli(t), the membrane mass m, mechanical losses r, compliance of the suspension c, and the acoustical load, which is seen through the transformer S:1.

Provided all loudspeakers are identical, and the two chambers perform as pressure chambers, each loudspeaker is loaded with volumes of $V_1/16$ at one side and $V_2/16$ at the other side. This load is given by the acoustical compliances c_1 and c_2. The pressure in the test chamber is indicated in the figure as $p_1(t)$.

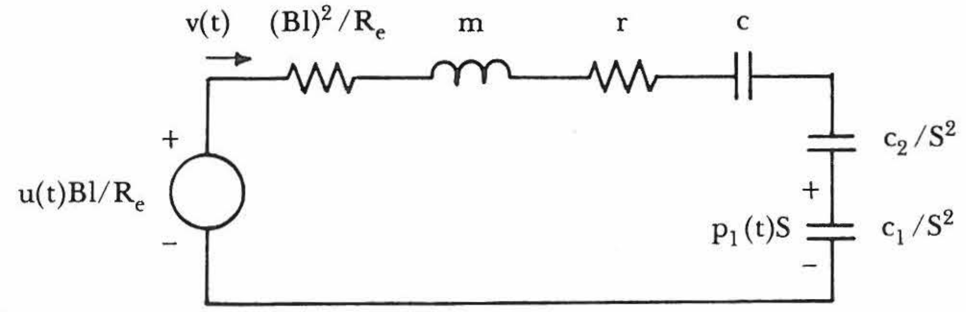

Figure 3. Equivalent diagram of the infrasound generating system, when all components are transferred to the mechanical side.

In figure 3 all elements are transferred to the mechanical side, and the transfer function from voltage at the loudspeaker terminals to sound pressure in the test chamber can now be derived. $P_1(s)$ and $U(s)$ denote the Laplace transforms of $p_1(t)$ and $u(t)$, respectively.

$$\frac{P_1(s)}{U(s)} = \frac{BlS}{R_e c_1 m[s^2 + s(r + (Bl)^2/R_e)/m + (1/c + S^2/c_1 + S^2/c_2)/m]}$$

This is a second order low pass filter with a gain:

$$\text{gain} = \frac{BlS}{R_e c_1(1/c + S^2/c_1 + S^2/c_2)}$$

The resonant frequency is given by:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1/c + S^2/c_1 + S^2/c_2}{m}}$$

and the Q factor by the expression:

$$Q = \frac{\sqrt{m(1/c + S^2/c_1 + S^2/c_2)}}{r + (Bl)^2/R_e}$$

If the actual values are inserted, gain = 6.8 Pa/V, f_0 = 30 Hz and Q = 0.41.

A low pass filter with an upper limiting frequency of 30 Hz is excellent as a transfer function in a chamber like this. However, it would be preferable if the frequency response were maximally flat in the pass band. This requires a Butterworth characteristic in which the Q factor is 0.707. This value could be achieved with a lower value of the Bl product of the loudspeakers, or by adding a series resistor to R_e, but none of these solutions are attractive from a power point of view.

Therefore an extra frequency equalizing filter has been introduced with two zeros cancelling the original poles and two new poles with Q factors of 0.707.

In figure 4 a block diagram of the complete system is shown. The power amplifier is a Brüel and Kjær Type 2712, 180 VA amplifier, which is able to drive the 16 loudspeakers combined in series-parallel to obtain a resistance of 1.4 Ω. The total gain is adjusted to 20 Pa/V, which means that 1 V gives a sound pressure level of 120 dB.

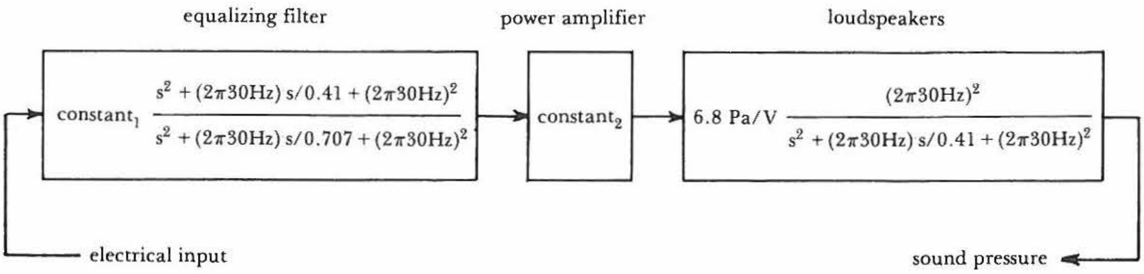

Figure 4. Block diagram of the infrasound generating system.

The transfer function is derived provided the test chamber and back volume perform as pressure chambers. This is not the case at frequencies above the infrasound range. Therefore, the low pass function can not be expected to be effective at higher frequencies, and a 4th order Butterworth low pass filter with an upper limiting frequency of 50 Hz is inserted before the power amplifier (not shown in figure 4). This prevents against electrical noise and higher frequencies accidentally connected. For the monitoring of the sound, a peak detector and a logarithmic level meter covering the range 70-130 dB is also installed.

Measurements of sound pressure and vibrations.

Figure 5 shows the sound pressure in the center of the room, when 1 V has been applied to the input of the system. As expected the frequency response is flat in a very wide range. There is a fall at higher frequencies, although the curve does not exactly follow a Butterworth characteristic. The deviations are due to the unequal sound distribution in the room.

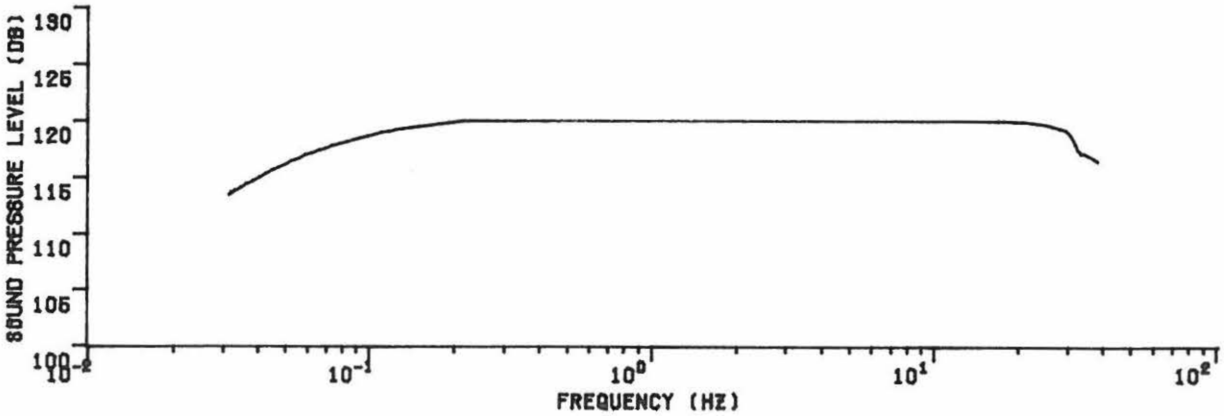

Figure 5. Sound pressure at the centre of the room, when 1 V is applied to the input of the system.

There is an unexpected decrease in sound pressure at very low frequencies. This is caused by the air leakage through the pores of the concrete walls. With no special care taken, a lower 3 dB point of 0.2 Hz was reached, and the value of 0.05 Hz in figure 5 was only reached after tightening with a thick layer of polyurethan paint on all surfaces.

In figure 6 and 7 the harmonic distortion is shown when the sound pressure level of the fundamental frequency is 120 and 125 dB respectively. At 120 dB both 2nd and 3rd harmonic distortion are more than 40 dB below the fundamental. Harmonics of higher order are not shown in the figure, but they are much below the levels of the 2nd and 3rd harmonics.

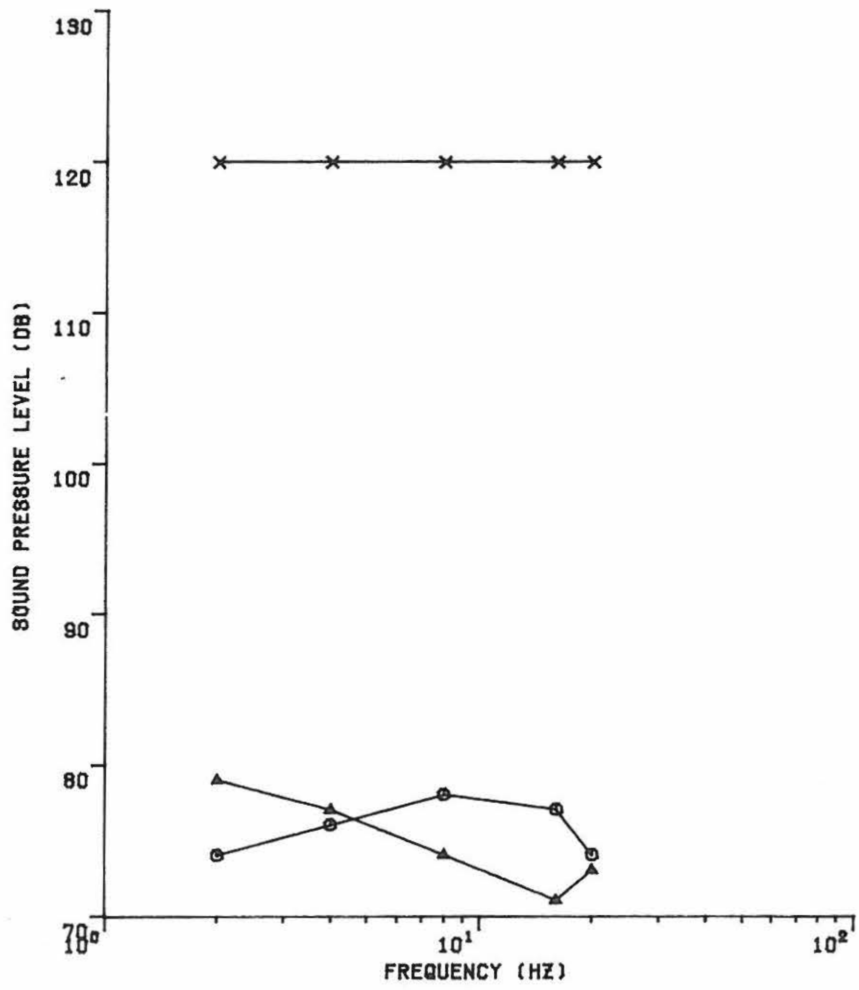

Figure 6. Harmonic distortion when the fundamental is 120 dB. Fundamental: ×, 2nd harmonic: ○, 3rd harmonic: △.

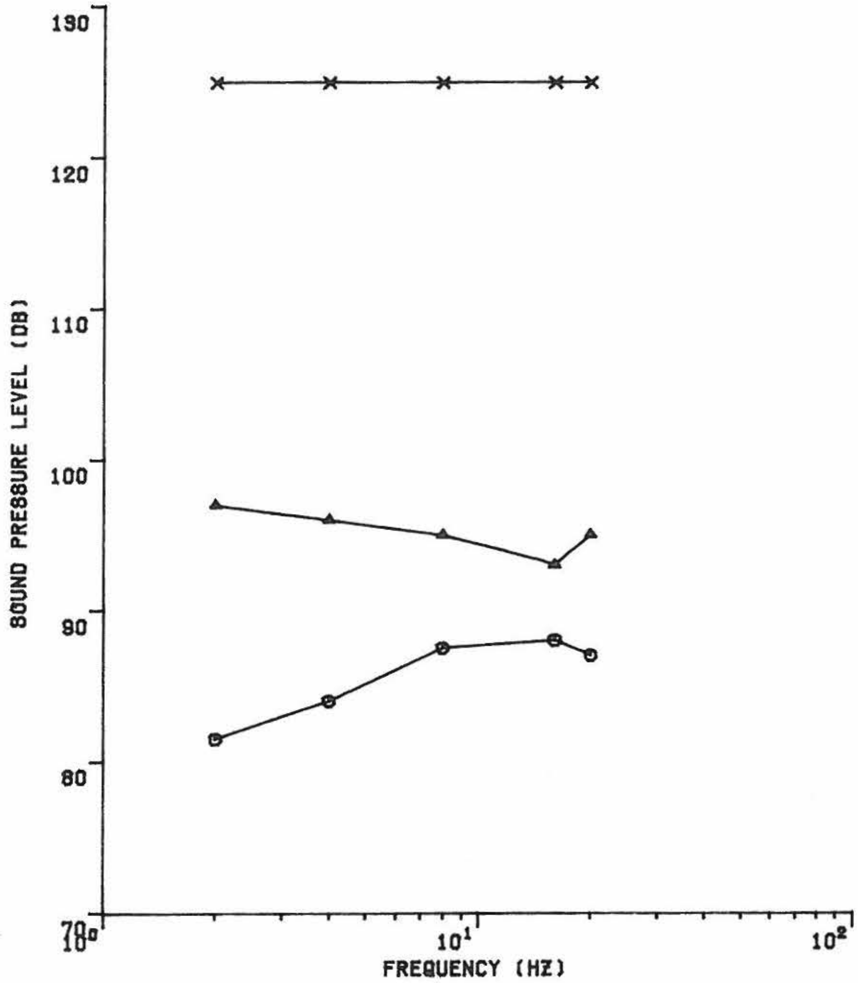

Figure 7. Harmonic distortion when the fundamental is 125 dB. Fundamental: ×, 2nd harmonic: ○, 3rd harmonic: △.

The results reached are very satisfactory. The threshold curve has a slope of approximately 13 dB per octave in this frequency range, and the low distortion easily ensures that the fundamental frequency is heard before the harmonics. Even at 125 dB, which is regarded as the upper limit of the dynamic range, the distortion is reasonably low.

In figure 8 the vibration level of a number of surfaces are shown, when the sound pressure level is 120 dB. The "reduced comfort boundaries for 8 hours exposure" of ISO 2631 are also shown. All curves except one, are much below the levels given in the standard. The only curve that approaches the level of the standard, is measured at the door, so subjects will not be exposed to it, and it can be concluded, that the vibration levels are satisfactorily low.

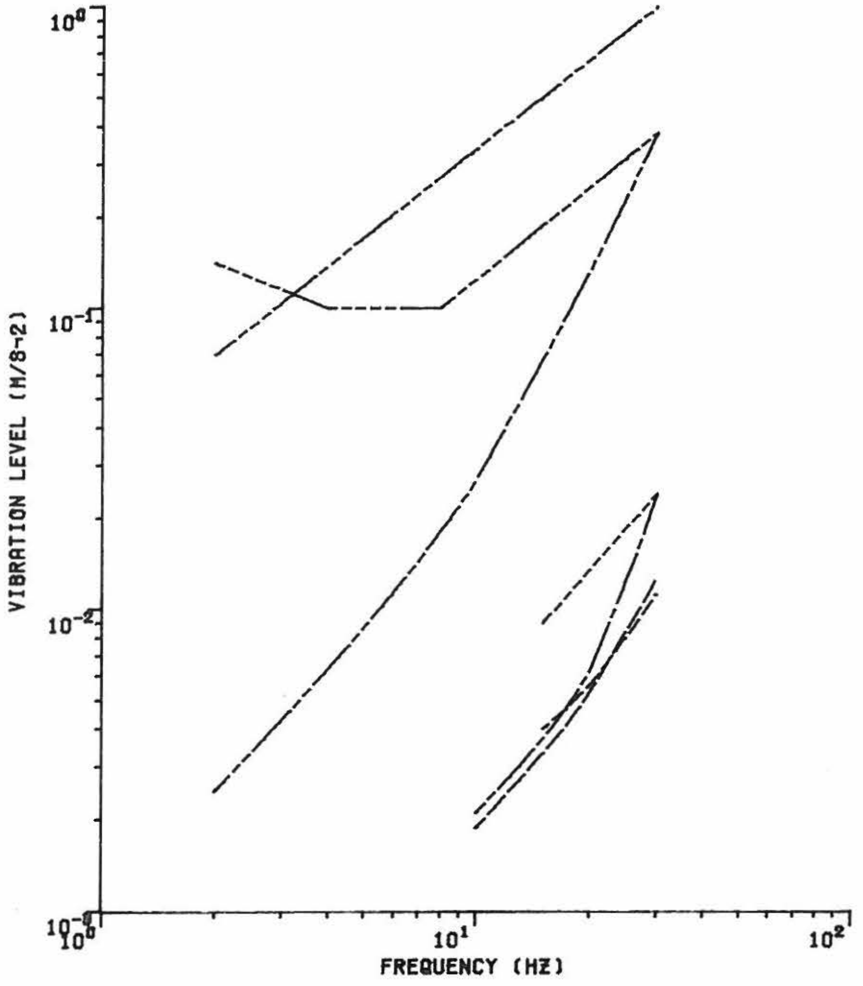

Figure 8. Vibration levels measured at surfaces in the test chamber as a function of frequency, when the sound pressure is 120 dB. Surface: ceiling: ----, floor: ----, wall: — — — —, wall: —-—-—-, door: —-·—-·—. Values are not shown at frequencies where the levels are at or below background level. Reduced comfort boundaries for 8 hour exposure, as given in ISO 2631, are also shown: vertical movements: —·-·—·-·—, horizontal movements: —·-·-—.

Sound distribution in the room.

Until now it has been assumed that the test chamber and the back volume perform as pressure chambers which means that the sound pressure is the same everywhere in the room. This assumption has been evaluated theoretically and by measurement.

in the calculations the model given in figure 9 has been used. The room is bounded by 5 rigid plans plus one plan where the loudspeakers are mounted. The latter is modelled by a rigid plan and a piston vibrating with a fixed amplitude. Thus the 16 loudspeakers are modelled by one big square covering the same total area and giving the same volume displacement.

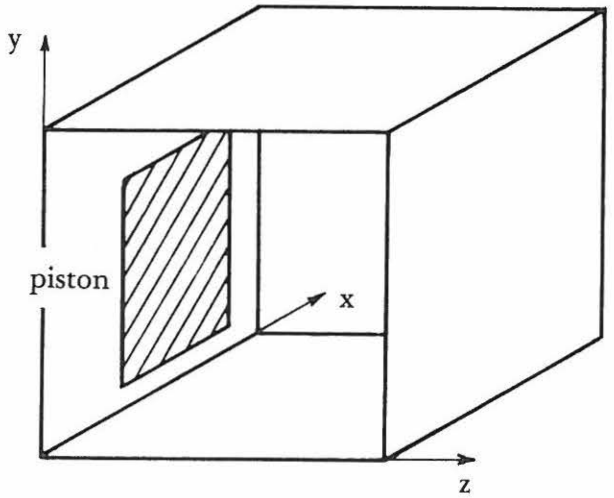

Figure 9. Model of test chamber used in calculation of the sound distribution in the room.

The calculations are given in [2] and will not be rendered here. They are based on the wave equation and the boundary conditions and they involve the description of the sound pressure as a sum of waveguide modes.

Figure 10 shows the sound pressure in a point in the room as a function of the frequency, assuming a fixed piston amplitude. At low frequencies the curve is flat corresponding to the assumption of a pressure chamber, while at higher frequencies resonancies and thus strongly varying sound pressure is seen. The first resonance is at 58 Hz, corresponding to a half wavelength in the direction of the x axis.

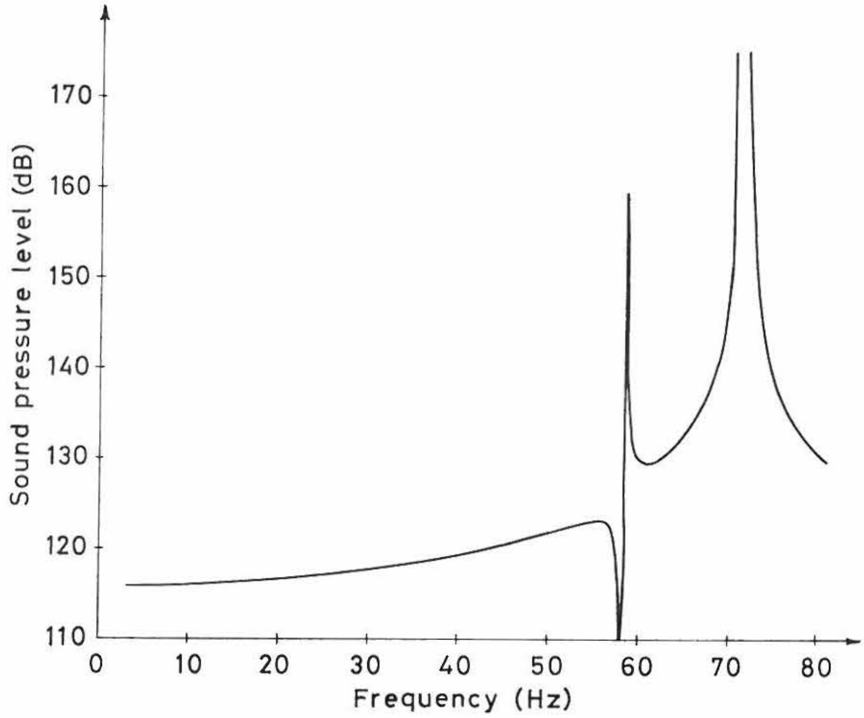

Figure 10. Calculated sound pressure at a fixed point (x,y,z) = (1.5 m, 1.5 m, 1.5 m) as a function of frequency, when the vibration amplitude of the piston is held constant at a level of 2 mm peak to peak.

In figure 11 and 12 the frequency is held constant at 10 Hz and the pressure is seen along two axis in the room. Both calculated and measured values are shown, and there is a good agreement between these. The variations in the room at 10 Hz are in the order of 1.5 dB, and will hardly cause any troubles. At 20 Hz and 30 Hz variations are below 3 dB and 8 dB respectively, provided a 30 cm space nearest to the loudspeakers is omitted. When making very accurate measurements like threshold and loudness determinations, it will be necessary to use a well specified position of the subjects.

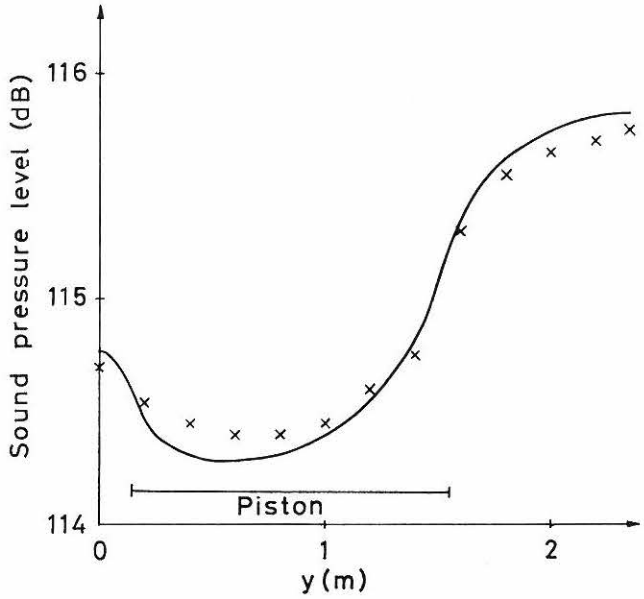

Figure 11. Sound distribution along the axis (x,z) = (1.5m, 0). The solid line is calculated, while points are measured values.

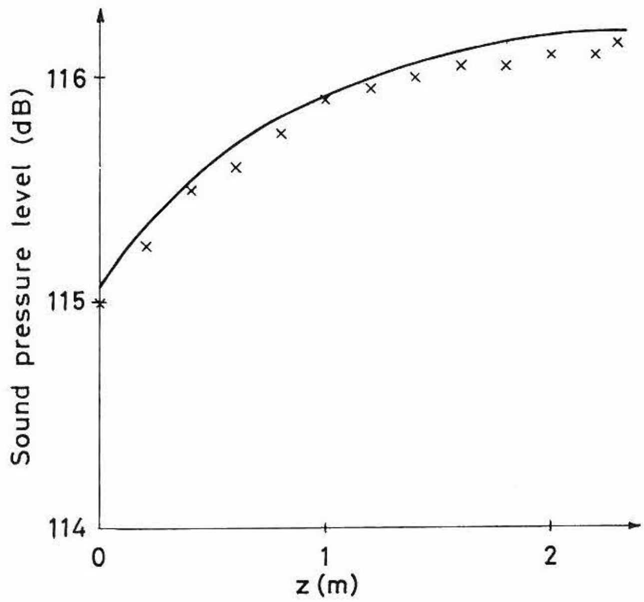

Figure 12. Sound distribution along the axis (x,y) = (1.5m, 1.5m). The solid line is calculated, while points are measured values.

Ventilating system.

The room is intended to be used for experiments of several hours duration, and some kind of supply of fresh air must be provided. A normal ventilating system can not be used, since it would enable the infrasound to vanish through the ventilator.

The chosen solution involves a high pressure ventilator and two flow resistances, one leading from the ventilator to the test chamber and the other from the chamber to the ambient, see figure 13.

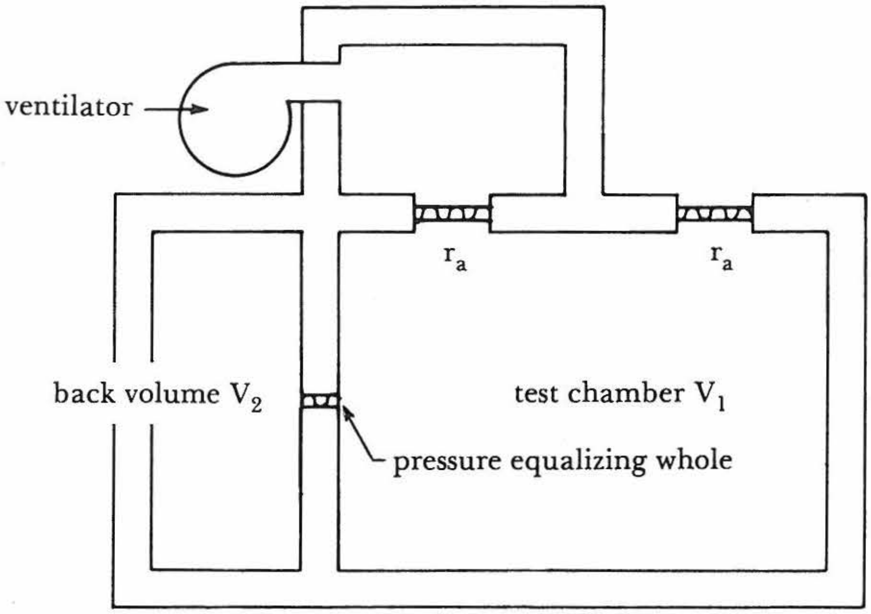

Figure 13. Schematic drawing of the ventilating system.

Also this system introduces a leakage, but the value can be controlled by the acoustic impedance of the leakages r_a. An equivalent diagram is given in figure 14.

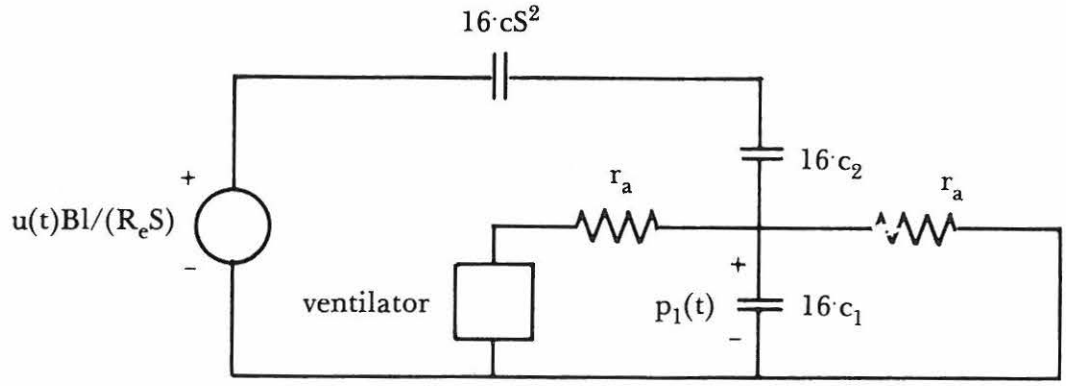

Figure 14. Equivalent diagram of the leakage introduced by the ventilating system. All components are transferred to the acoustical side. The 16 loudspeakers are modelled only by their compliance, since the membrane mass and the mechanical and electrical losses can be ignored at very low frequencies.

Assuming the ventilator to be an acoustic short circuit to the ambient, the lower 3 dB point will be $f_l = 1/[\pi r_a \cdot 16 \cdot (c_1 + c_2 cS^2/(c_2 + cS^2))]$. If $f_l = 0.3$ Hz is inserted, r_a becomes $8 \cdot 10^3$ Nsm^{-5}. This flow resistance is made by a 30 cm · 30 cm sheet of 5 cm rock wool.

The needed pressure P from the ventilator can be calculated from the wanted air exchange Q. For 3 persons Q should be around 60 m^3 per hour, or 0.017 m^3/s. Then $P = 2 \cdot r_a Q = 272$ Pa.

The solution chosen results in an overpressure in the test chamber of 1/2 of the supply pressure. This is a very small pressure and does not cause any troubles, except that an equalizing whole had to be made from the test chamber to the back volume, in order to prevent the loudspeakers from being pressed away from their equilibrium.

Unfortunately the ventilator itself generates some noise, including infrasound. Therefore an acoustic filter has been installed. The filter simply consists of a 0.86 m^3 box inserted between the ventilator and the flow resistance leading to the chamber. The box and the flow resistance together form a first order low pass filter. With the filter the noise from the ventilator is below the hearing threshold up to 50 Hz. At 63 Hz and above the ventilator only contributes little to the total background noise in the building, see figure 15.

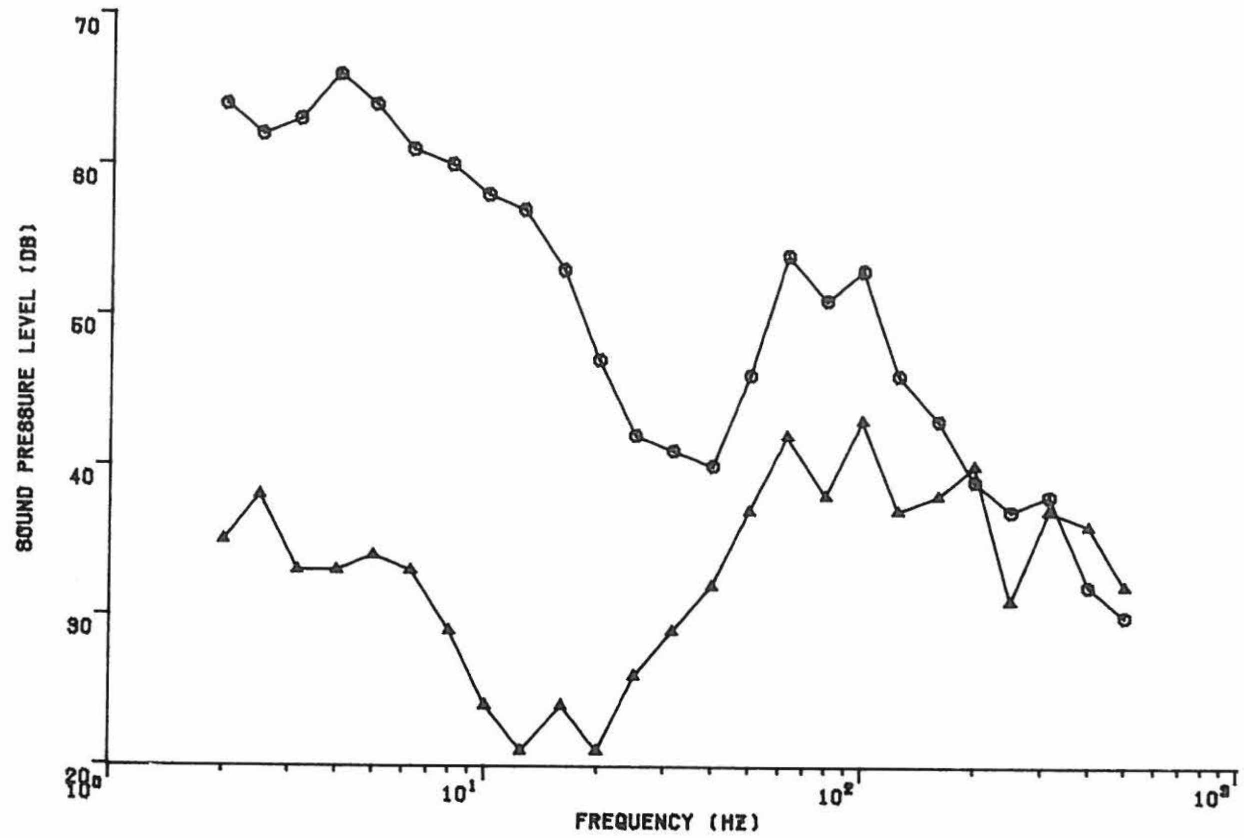

Figure 15. Background noise in the test chamber with (○) and without (△) ventilating system turned on. The values without ventilating vary a lot depending on other activities in the building, and it is only possible to obtain these values outside normal working hours.

The two room construction used in this laboratory in principle ensures that no sound is radiated from the system. However, in practice some sound is transmitted to the surroundings. Figure 16 shows the sound pressure in a corner of the surrounding laboratory, when the sound pressure in the test chamber is 120 dB.

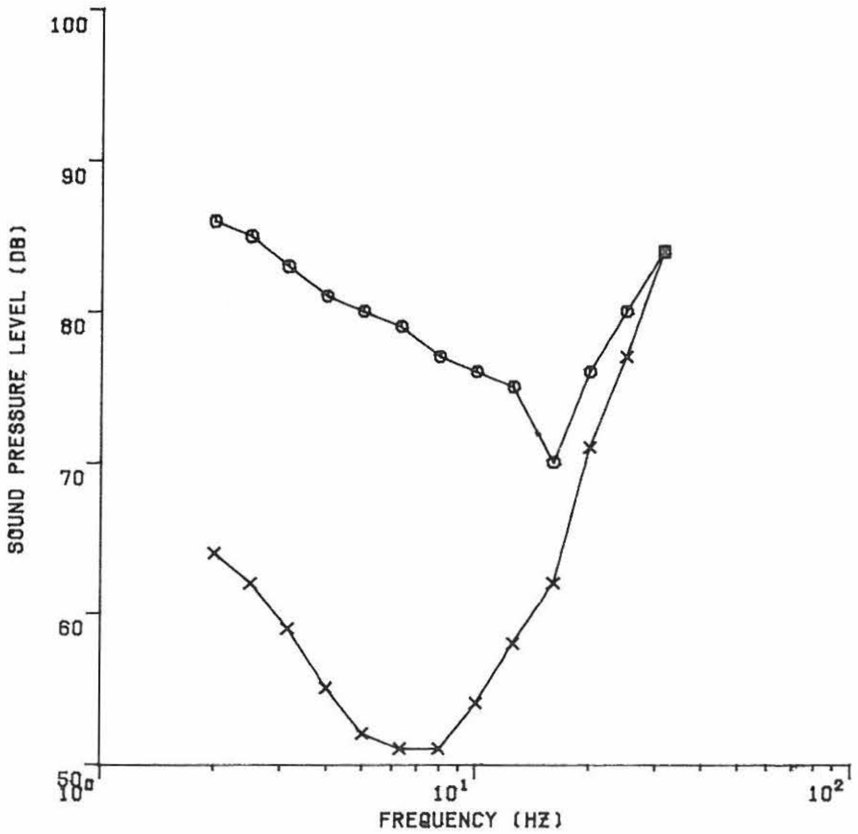

Figure 16. Sound transmitted to the surrounding laboratory when the sound pressure in the test chamber is 120 dB, and the leakages in the ventilating system are open (○) and closed (×).

With the ventilating system closed, significant radiation mainly occurs at high frequencies, where the walls vibrate. At low frequencies, the sound is transmitted through the air leakages of the walls. When the ventilating system is open, an additional leakage is introduced, and the transmitted sound increases considerably.

Although some sound is transmitted from the infrasound generating system to the surroundings, this is not expected to be a problem. The levels shown in figure 16 are only audible above 20 Hz approximately, and they are measured at a sound pressure level in the chamber near the upper limit of the dynamic range.

Conclusion.

In the test chamber described, it is possible to make experiments where human subjects are exposed to pure infrasound and low audio frequency sound in the frequency range 0.05 to 30 Hz. The chamber has a size, which allows two or three subjects to be under test at a time, and a ventilating system makes it possible to carry out experiments of several hours duration.

The maximum obtainable sound pressure level - 125 dB rms - is sufficient to cover most of the usually occurring environmental infrasound. If a higher sound pressure level is needed, the back volume can be used, since the sound pressure level here is approximately 10 dB higher because of the smaller volume. However, the back volume has no ventilating system, and it does not appear as pleasant as the test chamber itself, so only short time exposures will be carried out here.

The frequency range of the system covers the most important part of the infrasonic range, and it gives an overlap to the audio range. Extensions downward in frequency can only be made by excessive tightening of the walls. Upward in frequency we are restricted by the dimensions of the room, which should be small compared to a wavelength to keep a pure pressure field. Of course, a signal of a higher frequency than 30 Hz can be fed to the loudspeakers, but the sound pressure will then not be the same everywhere in the room.

Unwanted effects from the infrasound generator such as vibrations, harmonic distortion and audio frequency noise have been kept so low that they are not expected to influence the experiments.

Acknowledgements.

The author wishes to thank his colleagues for their advice and encouragement during the building of the chamber. Especially professor, dr. techn. Jørgen Bach Andersen and associate professor, M. Sc. Per Rubak have been a great help. The work was financed by Aalborg University.

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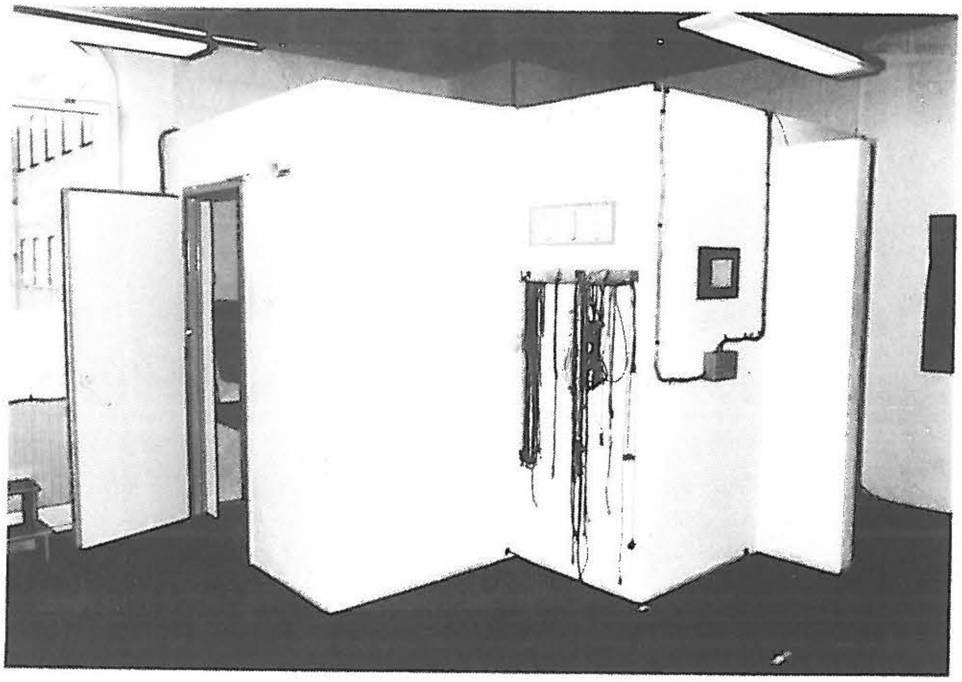
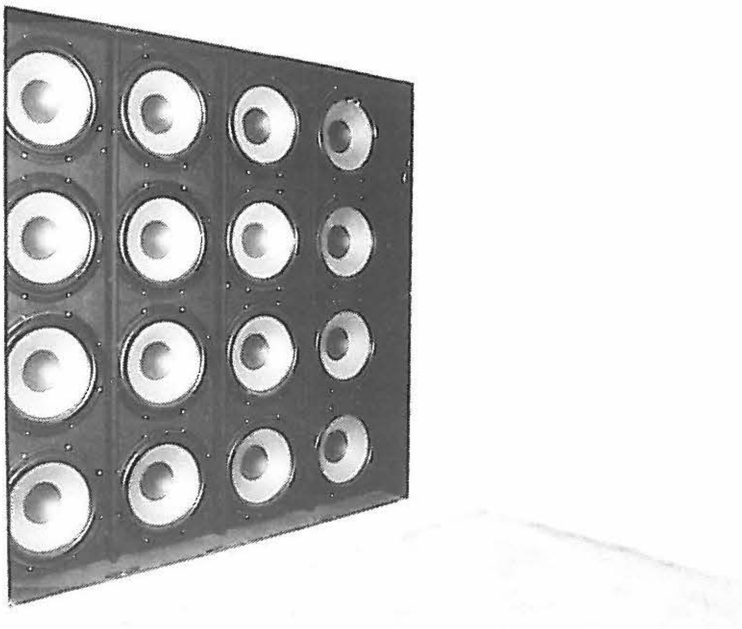
[1] Henrik Møller: Construction of an Infrasound Test Chamber. (In Danish). R 77-8 Institute of Electronic Systems, November 1977.

[2] Jørgen Bach Andersen: Variation of Pressure in the Cabin. Chapter 10 in [1].



The infrasound chamber is built of concrete in a corner of the laboratory. The open door leads to the back volume, while the door to the test chamber is hidden behind the wall to the right.



The infrasound is generated by 16 electrodynamic loudspeakers mounted in a wall. During the experiments they are covered by a cloth.

Paper B

Physiological and psychological effects of infrasound on humans

PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF INFRASOUND ON HUMANS

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ABSTRACT

Sixteen subjects were exposed for three hours to inaudible infrasound, audible infrasound, traffic noise and a quiet control condition, while they performed various psychological tasks. Some cardiovascular and hearing parameters were recorded and after the experiments the subjects answered a questionnaire concerning their experiences during the noise exposure.

The most conspicuous effect of infrasound was a high rating of annoyance and a feeling of pressure on the ear at less than 20 dB above the threshold of hearing. No influence on the cardiovascular system was seen and the performance only deteriorated in one of nine tasks. Infrasound below the threshold had no effect.

It is concluded that a better knowledge of the hearing at low frequencies is required, the most urgent being an extension downward in frequency of existing curves of equal loudness and equal annoyance.

1. INTRODUCTION

Infrasound is defined as acoustic waves with frequencies below 20 Hz, the frequency that is generally accepted as the lower limit of the normal hearing range. However, it has been shown that the human ear is able to detect infrasound, when the sound pressure is sufficiently high and threshold values at different frequencies have been determined (1, 2, 3, 4, 5).

Researchers and environmental authorities have also been interested in - and worried about - possible extra-auditory effects of infrasound. It is a widespread opinion that infrasound may cause disturbances of human body functions and influence the performance of humans. Often mentioned effects are changes in blood pressure, heart rate and respiration, disturbance of equilibrium, changes in production of stress-hormones and secretion of gastric juice, increase of reaction time and deterioration of performance in vigilance tasks.

The experimental evidence is, however, rather sparse. Only few experiments have been carried out and the results of these are not concordant. Furthermore, most of the studies have used only relatively short exposure times (2-60 minutes). In particular, there is a lack of information about long term effects of the most common infrasound, that below and just above the hearing threshold.

In the present investigation an exposure time of three hours was chosen and the exposures were infrasound just below and slightly above the hearing threshold. Also, a traffic noise sound condition was included in order to make it possible to compare the effects of infrasound with those of a well known sound. The recordings were performance in nine different tasks, some cardiovascular and hearing parameters and the subject's own experiences expressed through a questionnaire.

The investigation described in this paper was finished in 1980, and some of the results have already been published (6, 7). This is the first complete presentation.

2. METHOD

2.1 Subjects
Sixteen paid volunteers participated in the experiments, eight men and eight women. Fifteen were between 20 and 28 and one was 43. The subjects were all healthy and had normal hearing within ±20 dB at the octave frequencies from 125 Hz to 8 kHz.

2.2 Testroom
The experiments were carried out in a 16 cubic metre infrasound test chamber, where the infrasound was produced by 16 electrodynamic loudspeakers. The frequency response of the generating system was flat from below 1 Hz to nearly 30 Hz and the maximum obtainable sound pressure level was 125 dB rms. The harmonic distortion was kept very low to ensure that the exposure was purely infrasonic. The vibration level of the walls and the floor were also low enough to prevent against effects from these. A detailed description of the room has already been published (8).

The test chamber was equipped with a ventilating system which gave sufficient air exchange for the subjects (60 cubic metres per hour). However, no air conditioning possibilities existed as the air was simply taken from the surrounding laboratory. Air temperature, humidity of the air and atmospheric pressure were recorded during the experiments. Some fluctuations did occur, but they were not systematically related to any of the sound conditions. The ranges were: temperature: 20-24 °C, relative humidity: 35-55%, atmospheric pressure: $0.981-1.038 \cdot 10^5$ Pa.

2.3 Sound conditions
Four sound conditions were used: infrasound at two intensity levels, traffic noise and a quiet control condition.

Infrasound (Sound conditions C and D). It is reasonable to expect possible effects to be dependent on frequency and amplitude of the infrasound. Some investigations have even suggested certain pure tones as being especially dangerous (9, 10). There is, however, some disagreement about the frequency of these tones and it must be admitted that the scientific evidence of especially blaming certain frequencies is rather sparse.

Random noise in the infrasonic frequency range was chosen. This kind of noise includes all frequencies and thus also all the above mentioned "especially dangerous" frequencies. The origin of the noise signal was frequency limited white noise, but if this signal had been used directly, then the upper part of the spectrum i.e. frequencies near 20 Hz would have been very loud compared to the lower frequencies due to the slope of the hearing threshold curve. An attempt was therefore made to make the low and high frequencies equally audible by introducing a compensating filter that shaped the spectrum of the sound along the hearing threshold curve. For a one-third-octave analysis this was effective from approximately 6.3 Hz to 31.5 Hz thus covering the part of the infrasonic range that is most likely to have some effect and also giving a minor overlap into the audio region.

A pilot study with a few subjects served to determine two levels of this frequency-shaped infrasound to be used as exposures. The lower level (Sound condition C) was chosen as the highest possible level where the signal was still inaudible. This level was included since many of the worries about infrasound have concerned the possibility of having inaudible acoustic waves affecting people. The higher level (Sound condition D) was chosen to be 20 dB above the lower level and in the pilot study, it was characterized as loud and annoying. Spectrum analysis of the sounds are given in Figure 1.

Traffic noise (Sound condition B). This was recorded in a main street in Aalborg and reproduced by ordinary high fidelity equipment. The playback level chosen resulted in an A-weighted continuous equivalent level of 70.9 dB. The fluctuating properties of the noise are expressed by the following statistical measures: L_{10} = 74.3 dB(A), L_{50} = 69.3 dB(A), L_{90} = 63.0 dB(A), L_{95} = 60.8 dB(A).

Quiet (Sound condition A). This sound condition was used as a control. The background noise level was around 35 dB(A).

2.4 Questionnaires

A questionnaire with 12 questions was given at the end of each experiment. Each question was followed by a 165 mm horizontal line, of which the ends were labelled with possible but extreme answers to the question. An example is shown in Figure 2. The questions were answered with a cross at the line at the place where the subject felt that his answer could be represented. All positions were allowed. The questions are shown in Table 1 together with the labels of the answering lines. For Question 1 and 9 a midpoint labelled "neutral" was also given.

Some of the questions concerned the air in the test chamber and as the atmospheric properties were not varied intentionally (see section 2.2), these questions were only included to prevent the subjects from focusing on possible effects such as headache and dizziness.

The answers to the questions were read in percents of the answering line with a resolution of 5% and with 0% at the left end of line.

Table 1.
Questions and labels of the corresponding answering lines.

1. How did you find the air?
   (much too cold - neutral - much too warm)
2. Have you felt draught?
   (not at all - a lot)
3. Have you felt dizziness?
   (not at all - a lot)
4. Have the tests been tiring?
   (not tiring - very tiring)
5. How did you find the air?
   (heavy - fresh)
6. Have you felt nausea?
   (a lot - not at all)
7. Have you been annoyed by noise or rumble?
   (not annoyed - very annoyed)
8. Have you had a headache?
   (not at all - severe)
9. How did you find the air?
   (dry - neutral - moist)
10. How have you felt?
    (dull - fit)
11. Have you felt pressure on your ears?
    (a lot - not at all)
12. Do you find it annoying to sit in a small room like this?
    (very annoying - not annoying)

2.5 Physiological measurements
The physiological measurements were concentrated on the cardiovascular system and the hearing.

The systolic and diastolic blood pressure was measured with the ordinary arm-cuff method. The measurement was carried out at fixed minutes during each experiment as described in section 2.8.

The electrocardiogram was recorded on tape during fixed periods of the experiments. From each of these periods the interbeat-interval T was measured of 126 heartbeats corresponding to approximately two minutes. The mean of these 126 values of T was taken as representative of the interbeat-interval and it was registered in milliseconds. The change in T from beat to beat, ΔT, was also registered for the same 126 heartbeats. Since no change in activity took place during the two minutes measurement period, ΔT would have a mean close to zero. The standard deviation of ΔT was therefore registered as a measure of the minor adjustments of the interbeat-interval and it was denoted interbeat-variation.

A phonocardiogram was recorded during the same periods as the electrodiogram by means of a small microphone attached to the skin at the 4th or 5th intercostal room.

An audiogram covering the seven octave frequencies from 125 Hz to 8 kHz was taken before and after each experiment. A Madsen type OB 40 audiometer was used and at each frequency the hearing loss was measured with a resolution of 5 dB. The hearing loss was averaged over the seven frequencies to obtain the mean hearing loss, MHL. The influence of an experiment was calculated as ΔMHL = MHL(after) - MHL(before).

2.6 Task performance

Nine different tests were used. The tasks were presented either on a small film viewer or on a CRT-display terminal. Answers were given by pressing buttons. Some of the tests were developed at The Laboratory of Heating and Air Conditioning at The Technical University of Denmark, where they were used for measuring task performance during exposure to various conditions of temperature, humidity of the air and the like (11). For all tests the answering of one task was immediately followed by presentation of the next one.

Test 1: 5 three-digit numbers were presented together with three suggestions of the sum. The subject was to point out the correct sum or indicate that none of them were correct. The four possible answers were equally probable.

Test 2: Nine two-digit numbers were presented and the subject should indicate if they were all different. In 34% of the presentations two or more figures were identical.

Test 3: The subject was presented to various logical statements and requested to indicate whether the statement was right or wrong.

Examples:
A precedes B: AB (right)
After A is C: CA (wrong)
C does not follow B: CB (right)
A does not precede B: AB (wrong)

Test 4 was a cue utilization test, a modified version of the Tsai-Partington test (12). Encircled letters and numbers were shown and an arrow pointed out one of them. The subject was to indicate, whether the next sign could be found, when following the order 1-A-2-B-3-C-4-D etc. An example is given in Figure 3.

Test 5 was a test of short-term memory. A list of words was presented, one word at a time. Each word might occur more than once and at each word the subject was to respond whether he had seen it before.

Test 6 was a simple reaction time measurement. When a letter appeared in the centre of the CRT-display, a button was to be pressed. The time from an answer to presentation of the next stimulus was random and uniformly distributed in the range 2-6 seconds.

Test 7: Here the display was divided into five parts and the letter E appeared in one of them every 2 seconds. The subject should only react when the E appeared in the central part.

Test 8: The display was divided into two parts by a vertical line and the letters E and F appeared one at a time at either the left or the right side. The subject should react on an F to the left or an E to the right.

Test 9 was similar to Test 2, but it was carried out with the CRT-display terminal while the film viewer was used in Test 2.

The time the subjects spent on each of the tests is reported in section 2.8.

The distribution of the response time for a subject in a given test was found to be a logarithmic normal distribution rather than a simple normal distribution. Log(response time/1 second) was therefore used as the dependent variable and mean values were recorded for each experiment. Percents of errors were also recorded, except for Test 6, which was a simple reaction time test.

2.7 Experimental design

The 16 subjects were each exposed to the four sound conditions. The latin square in Table 2 was used to balance out order effects. Two subjects were exposed together and the same two subjects followed each other for the whole experiment. A subject was exposed at the same hour of the day every time.

Table 2.
The latin square design used in the experiment.

	treatment day			
subject	1	2	3	4
1-4	A	B	C	D
5-8	B	C	D	A
9-12	C	D	A	B
13-16	D	A	B	C

2.8 Procedure

For each experiment a strict time schedule was followed, see Figure 4. The first 30 minutes were used for an audiometric test, fixing of electrodes, etc. For the next three hours the subjects were seated in the test chamber while exposed to the sound.

During the sound exposure the subjects worked on the performance tests in accordance with the order and minutes given in Figure 4. Test 1-5 were given only once in each experiment, while Test 6-9 were given twice.

Recordings of the electrocardiogram and phonocardiogram were taken while the subjects worked on the performance tests, the first time after 30 minutes and thereafter with intervals of one hour. Blood pressure was also measured every hour, the first time after 50 minutes.

Just before the end of the exposure the questionnaire was given and after the exposure had ended, a new audiometric test was made and the electrodes were taken off.

2.9 Data analysis

For each dependent variable mean values were calculated for each of the four sound conditions. Also, a three-way analysis of variance was carried out with the following independent variables: sound condition (4 levels), treatment day (4 levels) and subject (16 levels). The latin square block design only allowed main effects to be included in the model. An SPSS program package was used for the analysis (13).

The cardiovascular variables were measured three times in each experiment. An additional independent variable, the time of measurement (3 levels), was included in the model along with the interaction term sound condition by time of measurement.

The phonocardiogram was recorded because earlier studies indicated the occurrence of additional heart sounds during infrasound exposure (not extra systoles) (14). The analysis was confined to listening to the recordings and watching them on an osscilloscope.

3. RESULTS

Mean values for all dependent variables at the four sound conditions are given in Table 3, while the significance levels obtained in the analysis of variance are shown in Table 4.

Table 3
Mean values of all dependent variables at the four sound conditions.

	Sound condition			
	A	B	C	D
Questionnaire:				
Question 1 (%)	50	53	41	40
Question 2 (%)	13	6	16	19
Question 3 (%)	9	21	8	11
Question 4 (%)	51	53	50	59
Question 5 (%)	61	49	64	53
Question 6 (%)	83	90	85	88
Question 7 (%)	10	82	11	70
Question 8 (%)	11	34	12	13
Question 9 (%)	43	46	48	44
Question 10 (%)	46	42	40	29
Question 11 (%)	88	83	93	51
Question 12 (%)	75	78	76	79
Physiological measurements:				
Systolic blood pressure (mm Hg)	120.4	119.4	120.3	120.5
Diastolic blood pressure (mm Hg)	77.6	77.8	75.7	75.8
Interbeat-interval (ms)	802	787	799	808
Interbeat-variation (ms)	47.7	41.8	43.6	43.0
ΔMHL (dB)	-2.8	1.7	-2.7	-2.0
Task performance:				
Test 1: log(response time/1 s)	1.31	1.31	1.31	1.34
errors (%)	11.6	10.4	11.5	9.8
Test 2: log(response time/1 s)	0.71	0.69	0.70	0.71
errors (%)	8.8	8.5	7.4	7.6
Test 3: log(response time/1 s)	0.61	0.58	0.57	0.61
errors (%)	4.1	2.9	3.6	4.1
Test 4: log(response time/1 s)	0.48	0.49	0.49	0.50
errors (%)	2.0	1.9	1.7	3.5
Test 5: log(response time/1 s)	0.16	0.14	0.14	0.16
errors (%)	8.4	7.9	6.9	7.1
Test 6: log(response time/1 s)	-0.57	-0.55	-0.56	-0.56
Test 7: log(response time/1 s)	-0.59	-0.58	-0.59	-0.56
errors (%)	0.4	0.4	0.2	0.5
Test 8: log(response time/1 s)	-0.31	-0.31	-0.32	-0.30
errors (%)	3.2	2.8	2.2	3.0
Test 9: log(response time/1 s)	0.58	0.53	0.56	0.56
errors (%)	6.6	7.3	6.3	8.5

Table 4
Significance levels obtained in the analysis of variance. Only significance at a level of 0.05 or higher is given. Terms not included in the model are indicated with '–'.

	main effects				interaction
	treatment day	subject	sound condition	time of measurement	time of measurement by sound condition
Questionnaire:					
Question 1	0.002	n.s.	0.042	-	-
Question 2	n.s.	<0.001	n.s.	-	-
Question 3	n.s.	<0.001	0.038	-	-
Question 4	0.037	<0.001	n.s.	-	-
Question 5	0.009	<0.001	n.s.	-	-
Question 6	0.042	<0.001	n.s.	-	-
Question 7	n.s.	<0.001	<0.001	-	-
Question 8	n.s.	<0.001	<0.001	-	-
Question 9	n.s.	n.s.	n.s.	-	-
Question 10	n.s.	<0.001	n.s.	-	-
Question 11	n.s.	<0.001	<0.001	-	-
Question 12	n.s.	<0.001	n.s.	-	-
Physiological measurements:					
Systolic blood pressure	0.002	<0.001	n.s.	0.025	n.s.
Diastolic blood pressure	<0.001	<0.001	n.s.	<0.001	n.s.
Interbeat-interval	n.s.	<0.001	n.s.	<0.001	n.s.
Interbeat-variation	n.s.	<0.001	n.s.	<0.001	n.s.
ΔMHL (dB)	n.s.	n.s.	0.006	-	-
Task performance:					
Test 1: log(response time/1 s)	n.s.	<0.001	n.s.	-	-
errors	<0.001	<0.001	n.s.	-	-
Test 2: log(response time/1 s)	<0.001	<0.001	n.s.	-	-
errors	0.033	<0.001	n.s.	-	-
Test 3: log(response time/1 s)	<0.001	<0.001	n.s.	-	-
errors	0.003	<0.001	n.s.	-	-
Test 4: log(response time/1 s)	<0.001	<0.001	n.s.	-	-
errors	n.s.	n.s.	0.016	-	-
Test 5: log(response time/1 s)	0.010	<0.001	n.s.	-	-
errors	n.s.	<0.001	n.s.	-	-
Test 6: log(response time/1 s)	n.s.	<0.001	n.s.	-	-
Test 7: log(response time/1 s)	n.s.	<0.001	n.s.	-	-
errors	n.s.	<0.001	n.s.	-	-
Test 8: log(response time/1 s)	n.s.	<0.001	n.s.	-	-
errors	n.s.	n.s.	n.s.	-	-
Test 9: log(response time/1 s)	<0.001	<0.001	n.s.	-	-
errors	n.s.	<0.001	n.s.	-	-

Figure 5, 7 and 10 illustrate dependence on sound condition, while variation with treatment day is shown in Figure 6, 8 and 11. Figure 9 shows dependence on time of measurement for the cardiovascular parameters.

In the phonocardiograms there were no unusual observations like extra sounds.

4. DISCUSSION

4.1 Questionnaires

Effects of sound condition. For Questions 1, 3, 7, 8 and 11, there is a significant effect of sound condition. This is illustrated in Figure 5.

Question 1 concerns the temperature of the room. It is seen from Figure 5 that the air is perceived as colder during infrasound exposure compared with the other conditions. The effect is surprising. A possible explanation is that the motion of the air due to the sound increases the convective heat transport from the body to the air. A rough estimate of the air velocity is 0.1-0.2 m/s rms near the loudspeakers at sound condition D. It cannot be excluded that this motion of air makes it feel colder, but because of the small difference between condition C and D and accounting for the low significance level, the effect is believed to be a type 1 error.

Question 3 deals with dizziness. From Figure 5 it can be seen that a slightly higher degree of dizziness is obtained at sound condition B than at A, C and D. Thus the traffic noise causes higher ratings of dizziness than both of the infrasound conditions and the quiet sound condition.

The annoyance felt from noise or rumble is judged in Question 7. It is obvious that ratings at A and C are very low and approximately the same, while both B and D cause high values. This means that the subjects are very annoyed by the traffic noise and the audible infrasound. Ratings for A and C are not exactly zero, probably due to noise from other activities in the building.

Question 8 deals with headache. Some headache is experienced in all sound conditions, but the rating for sound condition B is clearly higher than for the other conditions. Thus traffic noise results in an increased occurrence of headache, while neither audible nor inaudible infrasound does.

A feeling of pressure on the ears (Question 11) is found at sound condition D (note that the labelling of the answering line is reversed in this question). It is not clear whether this feeling is caused by a real middle ear pressure build-up, or the subjects simply express their perception of infrasound in this way. A better wording of the question should be considered for future investigations.

Effects of treatment day. A significant effect of treatment day is found for Question 1, 4, 5 and 6. This is illustrated in Figure 6.

Question 1 and 5 concern the air in the room, which is perceived as colder and more fresh from the first time a subject participates towards his fourth and last participation. The physical fluctuations in air temperature, humidity of air and atmospheric pressure were small and there was no general trend from the beginning to the end of the experimental period. The effect is hardly a chance effect considering the significance levels and the agreement between the answers to the two questions. The change in perception can be explained as an adaptation effect.

Results from Question 4 "Have the tests been tiring?" show a generally falling tendency with time. In particular, ratings from the last day are lower than from the others. A possible explanation is that the tests become more acceptable towards the end of the experiment and especially at the last day.

Question 6 is "Have you felt nausea?" and the results indicate an increased feeling of nausea when the subjects participate for the third time. The significance level is only 0.042 and no reasonable explanation of the phenomenon can be given.

4.2 Physiological measurements

Effects of sound condition. The only parameter that is significantly influenced by sound condition is ΔMHL. The dependence is shown in Figure 7.

The value of ΔMHL is approximately 4 dB higher at B than at the other sound conditions, indicating that the traffic noise introduces a TTS. A detailed analysis has shown that the TTS is broadband.

It is also seen that the values at sound conditions A, C and D are negative. This means that the hearing of the subjects becomes better during the experiments, except when the exposure is traffic noise. An explanation may be that the subjects arrive for the experiments with a minor temporary threshold shift (TTS), for example caused by traffic noise on their way to the laboratory.

Effects of treatment day. Systolic and diastolic blood pressure is significantly dependent on treatment day and higher values are seen at the first day, see Figure 8.

Effects of time of measurement. All cardiovascular parameters are dependent on time of measurement. Figure 9 shows that in the beginning of the experiment the blood pressures are lower, the pulse faster and the interbeat-variation lower than for the rest of the experiment.

Effects of treatment day and time of measurement are believed to be psycho-physiological and caused by the mere participation of the subjects in a scientific experiment.

4.3 Task performance.

Effects of sound condition. Only errors in Test 4 are significantly dependent on sound condition and Figure 10 clearly illustrates that there are more errors at sound condition D (audible infrasound) than at the other sound conditions.

Effects of treatment day. Many variables are significantly influenced by treatment day and the dependence is shown in Figure 11. It is obvious that the response time decreases with time. The average improvement in log(response time/1 s) from the first to the fourth time a subject participates is 0.114, which corresponds to a decrease in response time of 23%.

For Test 1 and 3 an improvement in performance is seen as the number of errors decreases with time, while in Test 2 an increase is seen. This increase may be chance (the significance level is only 0.033), but it may also indicate that the subjects change their priority from correctness to speed as the experiment proceeds.

4.4 General

For most of the dependent variables no effects of infrasound are seen. None of the cardiovascular parameters are significantly influenced by the infrasound and a significant deterioration of task performance is only seen in one test. From the questionnaires it should especially be noticed that no perceptions of dizziness, tiredness, nausea or headache are introduced by the infrasound.

The lack of significant effects of infrasound is in contrast to indications in a number of reports (9, 10, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31) but in agreement with several others (32, 33, 34, 35, 36). It is not the purpose of this paper to present a review of the literature, but the author wants to draw attention to the fact that most of the papers that mention severe extra-auditory effects of infrasound are survey papers. It is the opinion of the author that many of these can be criticised for their generalisations of sporadic and unsystematic findings of other authors. When effects are summarized, the original reservations are often forgotten and non-significant tendencies easily change into facts.

Much confusion is caused by misconceptions about the hearing of infrasound. It is not generally known that infrasound can be detected by the human ear. Therefore, true effects of audible and possibly loud infrasound are often reported as being caused by the "inaudible infrasound".

When a dependent variable in an experiment does not appear to be dependent on the treatments, there may be a true lack of dependence, or the choice of design and statistical analysis may be unsuitable to discover an existing dependence. In this connection, it should be noticed that only main effects have been considered in the present investigation. If some subjects are especially sensitive to infrasound, this will appear in the analysis as an interaction effect between subject and sound condition. In the present design where the subjects are exposed to each sound condition only once, this interaction cannot be tested. If such an interaction exists, it may even reduce the power of the test of main effects because the error variance will be estimated to be too large. A look at the significant main effects found for other variables (Figures 6, 8, 9, 11) may give an idea of the magnitude of effects that could be detected in the present experiment.

5. CONCLUSION

Infrasound slightly above the hearing threshold gave a feeling of pressure on the ear and it was given a high rating on an annoyance scale. The infrasound did not cause headache, nausea, tiredness or dizziness and did not influence the circulatory system. The subjects performance differed significantly from the control in only one of nine tests. No effects were observed from infrasound below threshold.

In the literature, extra-auditory effects seem to have been exaggerated while effects related to the hearing may have been underestimated. Therefore, a better knowledge is required about the hearing function at infrasonic frequencies. In particular, the fact that infrasound less than 20 dB above the hearing threshold was rated close to "very annoying" emphasises the need for curves of equal annoyance.

The hearing threshold curve has already been determined with reasonable accuracy (1, 2, 3, 4, 5) and some preliminary curves of equal loudness have been given (3, 37, 38, 39). Some introductory approaches to a frequency dependent limit based on a discomfort criterion have also been made (5, 40) and at Institute of Electronic Systems, experiments are being carried out to determine a complete set of equal annoyance curves (41, 42).

The exposure levels used in this investigation are somewhat below the maximum levels found in industry and transportation and additional experiments ought to be carried out at slightly higher levels. The validity of the results for older age groups should also be investigated.

The performance tests used in this investigation were all relatively simple and cannot be compared to demands that are made on, for example, bus or lorry drivers. Recent research has shown that mainly complex tasks - for example simultaneous work on two or more tasks - are influenced by ordinary noise (43, 44). In this experiment, no effect was even seen from traffic noise and future investigations ought to clarify whether the lack of effects is valid also for more realistic and complex tasks.

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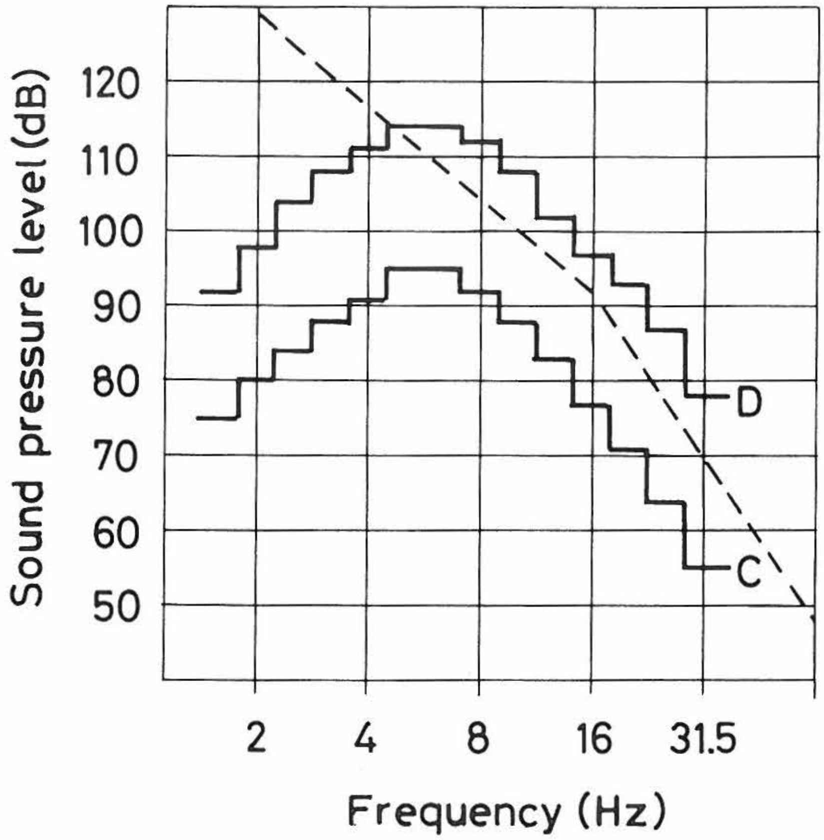

Figure 1.
One-third-octave analysis of the stimuli C and D. Total sound pressure level: C: 100 dB(lin.), D: 120 dB(lin.). The dotted line shows the threshold curve according to Yeowart et al. (4). The thresholds are given for pure tones, and levels should not be compared directly with the spectrum levels.

Have you felt dizziness ?

not at all a lot

Figure 2.
Example of a question with answering line.

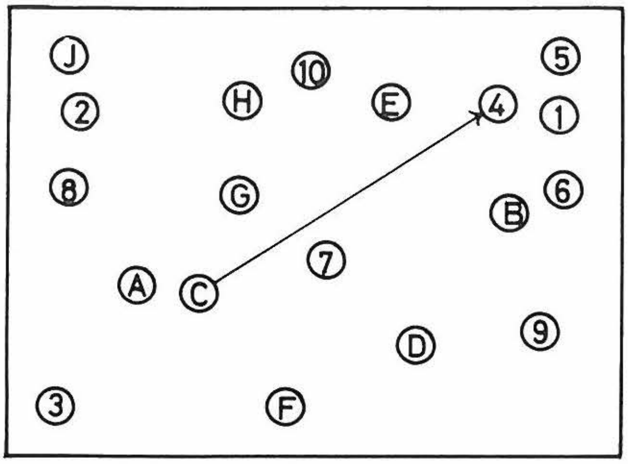

Figure 3.
Example of test 4. The arrow points out "4", and the next character "D" can be found.

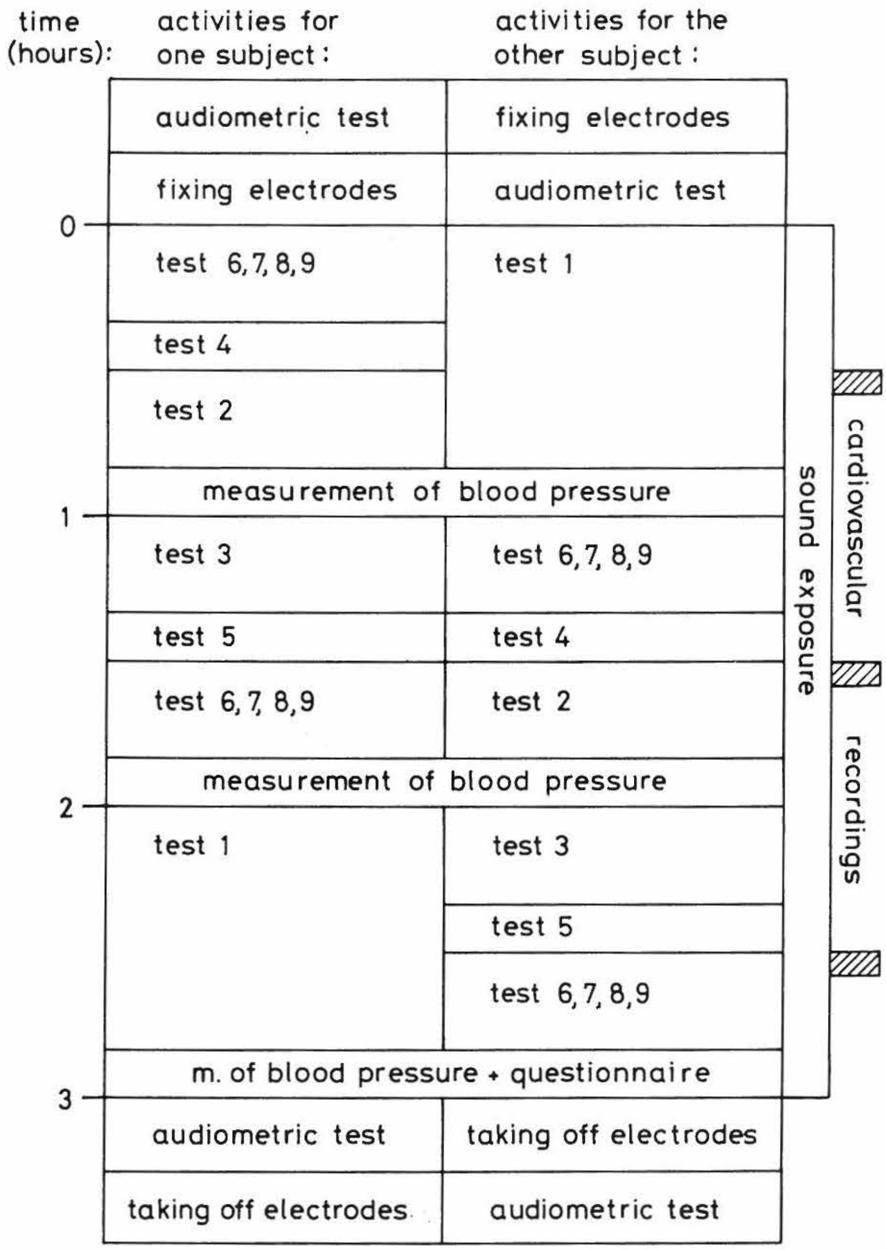

Figure 4.
Time schedule for an experiment.

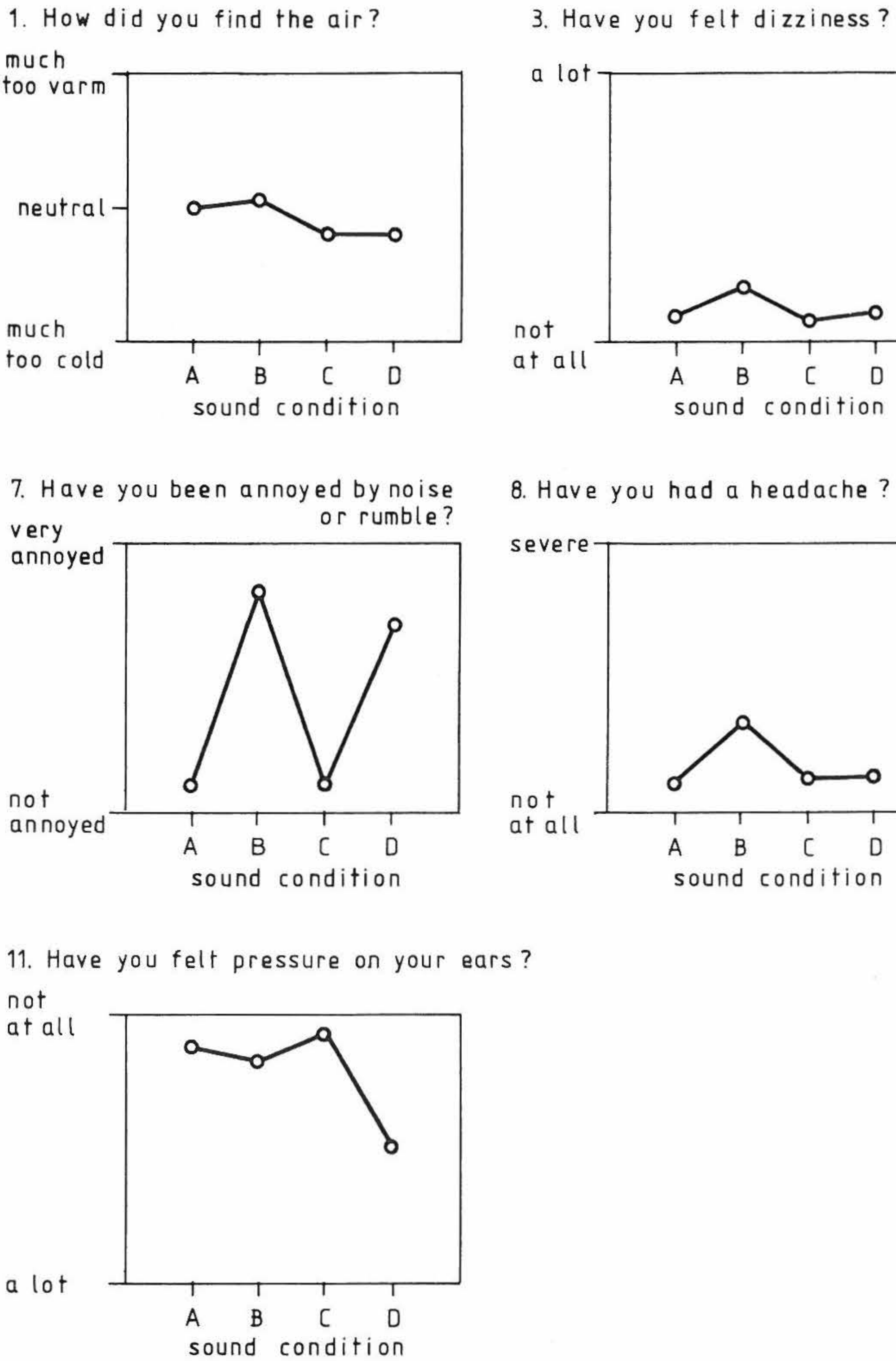

Figure 5.
Question 1, 3, 7, 8 and 11; means at the four sound conditions.
Significance levels: Question 1: 0.042; Question 3: 0.038;
Question 7: <0.001; Question 8: <0.001; Question 11: <0.001.

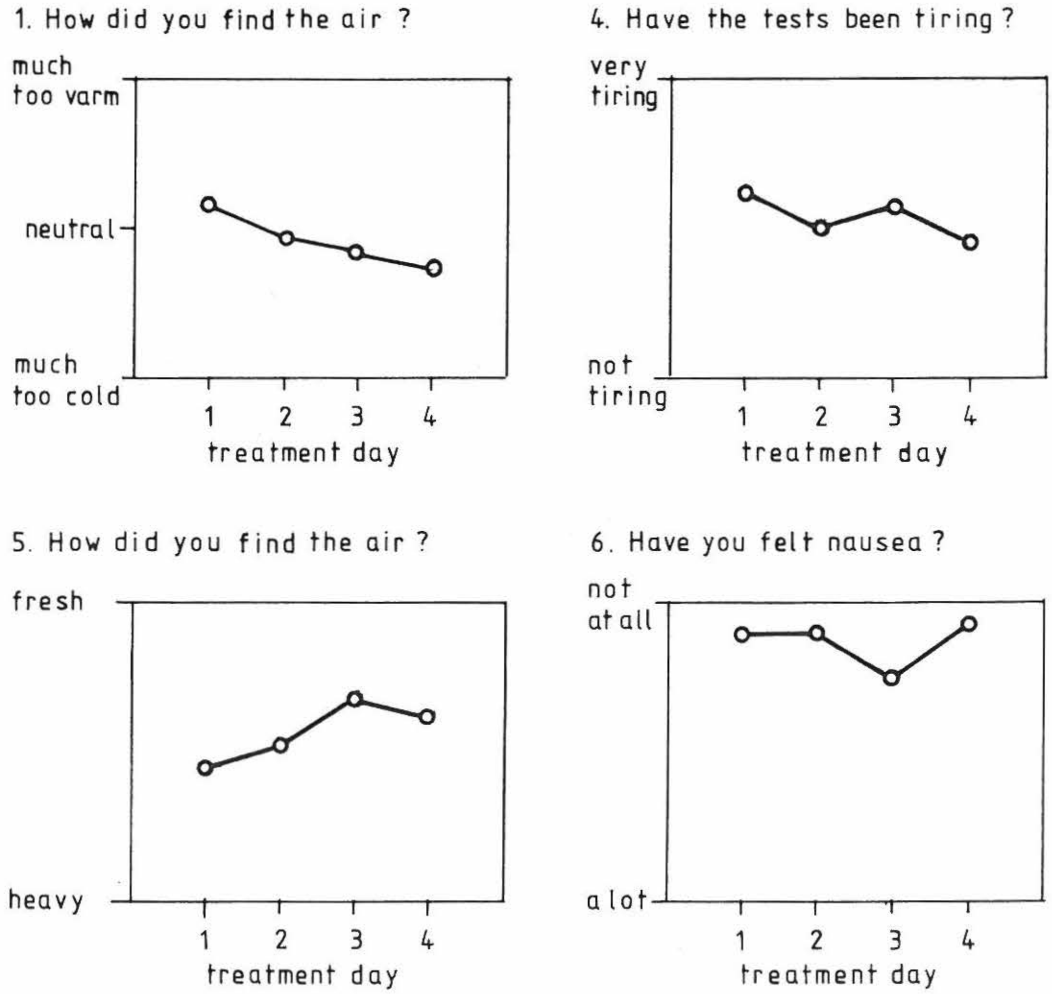

Figure 6.
Question 1, 4, 5 and 6; means at the four treatment days.
Significance levels: Question 1: 0.002; Question 4: 0.037;
Question 5: 0.009; Question 6: 0.042.

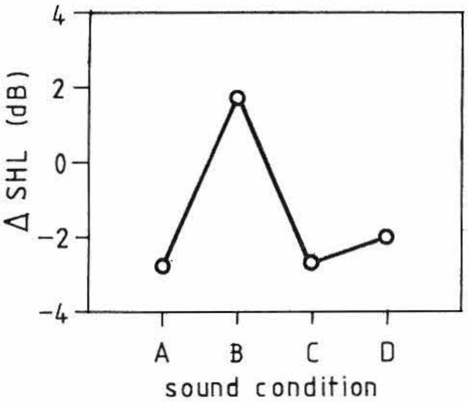

Figure 7.
ΔMHL; means at the four sound conditions. Significance level: 0.006.

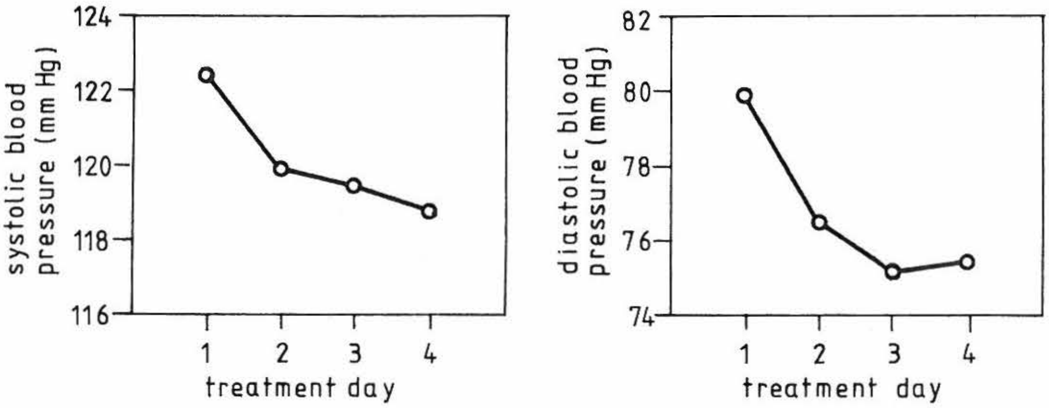

Figure 8.
Systolic and diastolic blood pressure; means at the four treatment days. Significance levels: systolic blood pressure: 0.002; diastolic blood pressure: <0.001.

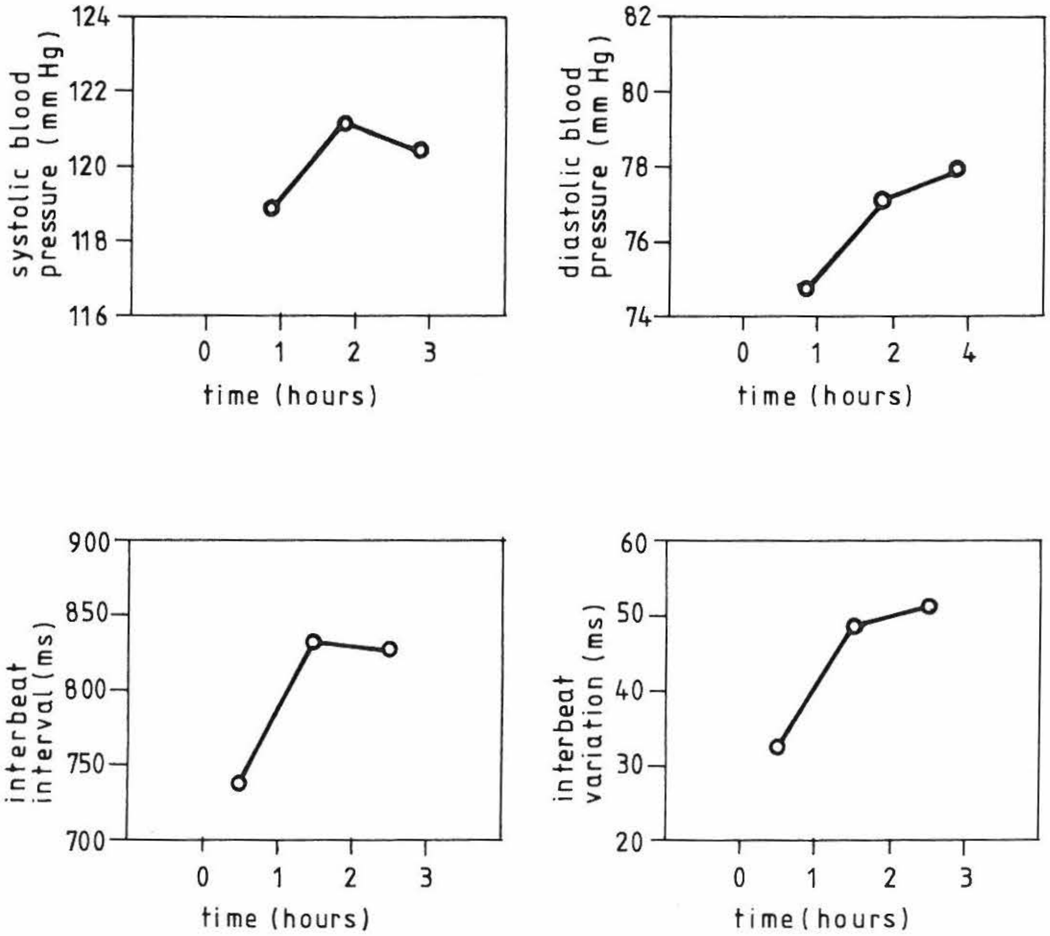

Figure 9.
Cardiovascular parameters; means at different time of measurement. Significance levels: systolic blood pressure: 0.025; diastolic blood pressure: <0.001; interbeat-interval: <0.001; interbeat-variation: <0.001.

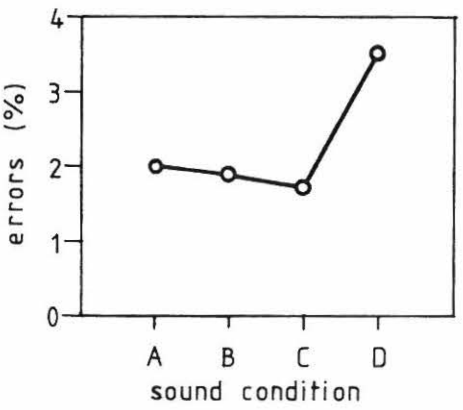

Figure 10.
Errors in test 4; means at the four sound conditions.
Significance level 0.016.

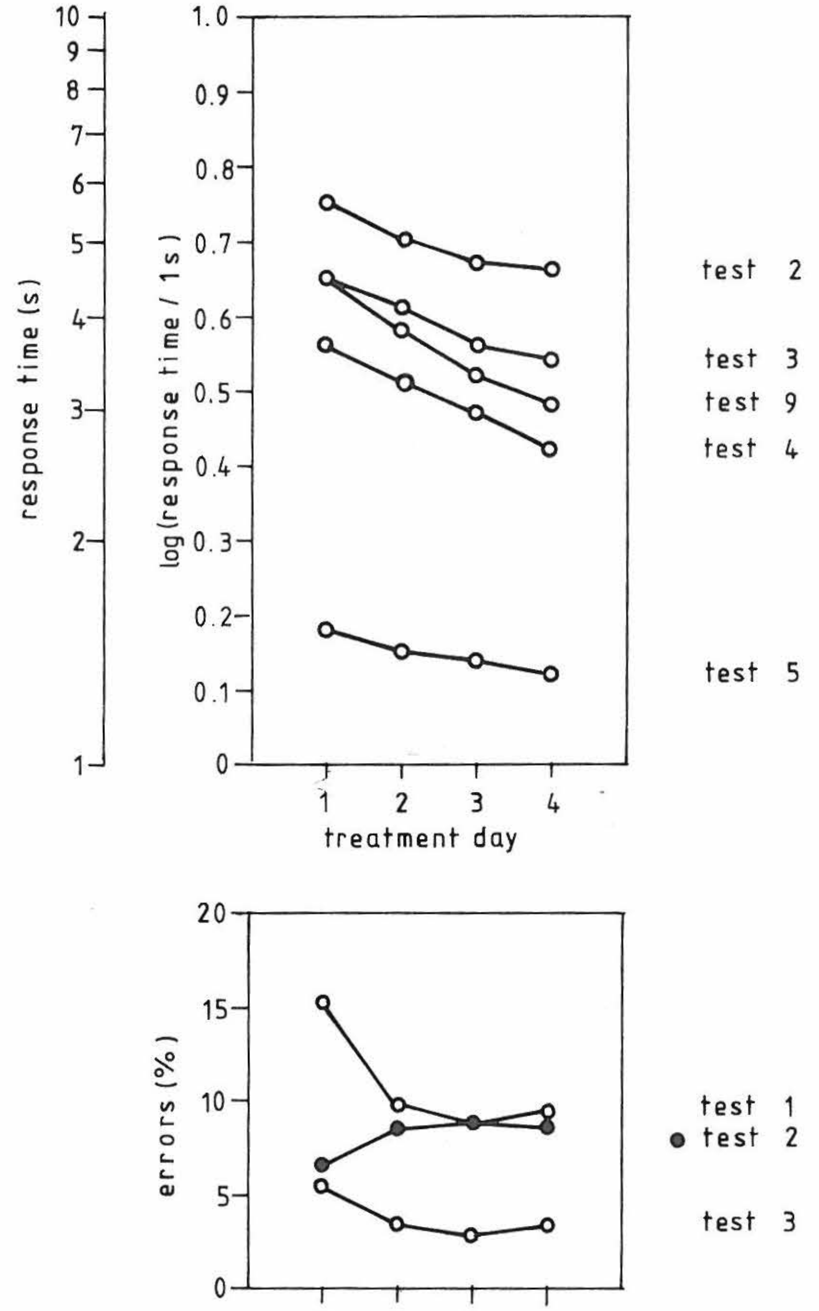

Figure 11.
Response time in Test 2, 3, 4, 5 and 9, and errors in Test 1, 2 and 3; means at the four treatment days. Significance levels: response time: Test 2: <0.001; Test 3: <0.001; Test 4: <0.001; Test 5: 0.010; Test 9: <0.001; errors: Test 1: <0.001; Test 2: 0.033; Test 3: 0.003.

Paper C

Loudness of pure tones at low and infrasonic frequencies

LOUDNESS OF PURE TONES AT LOW AND INFRASONIC FREQUENCIES

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ABSTRACT

Contours of equal loudness were determined in the frequency range 2-63 Hz and the loudness range 20-100 phon. The loudness curves run almost parallel in the infrasonic frequency range and much closer than in the audio region. Infrasound only a few dB above the hearing threshold will therefore seem loud and possibly annoying. The subjects were 20 normal hearing students aged between 18 and 25, and the psychometric method was based on maximum-likelihood estimation of psychometric functions.

1. INTRODUCTION

For nearly 20 years researchers and environmental authorities have been worried about possible extra-auditory effects of infrasound, such as disturbance of equilibrium and influence on the circulatory system. Experimental findings are not very concordant, but in general the effects seem to have been exaggerated (1).

However, lack of direct physiological effects from infrasound does not mean that infrasound is insignificant from an environmental point of view. Infrasound can be detected by the human ear, and when it becomes sufficiently loud, it can be annoying. Some investigations indicate that a possible "threshold of annoyance" would be only slightly above the hearing threshold (2, 3).

A number of experiments deal with the hearing threshold at infrasonic frequencies (2, 4, 5, 6, 7), but the loudness function has previously been the subject of only one investigation (5).

In the present study equal loudness curves were determined for pure tones in the frequency range 2-63 Hz and the loudness range 20-100 phon. Preliminary results from a pilot study were presented at Internoise 81 (8), and a report of the main experiment was given at Internoise 83 (9).

2. METHOD

2.1 Subjects

20 students (16 male and 4 female) aged between 18 and 25 participated as subjects. An audiometric test ensured normal hearing within ±15 dB at the octave frequencies 125 Hz to 4 kHz and ±20 dB at 8 kHz.

2.2 Stimuli

The references for loudness curves are pure tones at 1 kHz. However, it is very difficult to compare tones that are spaced as far in frequency as infrasound and 1 kHz, and in this investigation a supporting point was introduced at 63 Hz. Thus, individual points of equal loudness measured at 63 Hz were used as references for comparisons with 2, 4, 8, 16 and 31.5 Hz. Points of equal loudness were determined at 5 loudness levels: 20, 40, 60, 80 and 100 phon.

2.3 Psychometric method

A point on an equal loudness contour is determined through comparisons between a reference tone with a fixed sound pressure and another tone, of which the sound pressure can be varied. The task is to find the level of the variable, which makes the two tones seem equally loud to a listener. Unfortunately there is usually a range of several dB, where sometimes the variable, sometimes the reference appears to be loudest. Therefore some statistical procedure must be encorporated in the experiment. A modified version of the adaptive procedures based on maximum-likelihood estimation of psychometric functions as given by Hall (10) and Lyregaard and Pedersen (11) was chosen.

Figure 1 shows the psychometric function. This function gives the relation between the variable level and the probability of the subject perceiving the variable louder than the reference. The psychometric function is assumed to be a cumulative normal distribution with mean μ and standard deviation σ. μ represents the point of equal loudness, while information about the size of the area of uncertainty can be obtained from σ.

A point on an equal loudness curve was determined in the following way: Successive pairs of reference and variable tones were presented to the subject. The tones had a duration of 2 seconds and were separated by an interval of 1 second. The order in which they appeared was random. After each pair of tones the subject indicated which one he perceived as loudest, and μ and σ were estimated by means of the method of maximum-likelihood (12). Then a new variable level was chosen for presentation, and the procedure was repeated several times, until the estimated parameters were believed to be sufficiently exact. A flow chart is shown in Figure 2.

A maximum-likelihood estimation of the psychometric function is only possible, when at least one level is known where the variable is perceived louder than the reference and one where it is perceived softer. A special start procedure is therefore necessary. The first level presented was the experimenter's best guess at the point of equal loudness. If the subject found the variable louder than the reference, then the variable level was decreased by 10 dB for the second presentation, while it was increased by 10 dB, if the subject found it softer. Usually the second judgement was the opposite of the first, and the experiment was continued according to Figure 2. If the two answers were identical, the experimenter had to make a new guess.

In order to obtain a reasonable amount of information from each answer, the levels presented were chosen in the region of uncertainty. The 5 values $\hat{\mu}-2\hat{\sigma}$, $\hat{\mu}-\hat{\sigma}$, $\hat{\mu}$, $\hat{\mu}+\hat{\sigma}$ and $\hat{\mu}+2\hat{\sigma}$ were given equal probability; levels already given were however excluded ($\hat{\mu}$ and $\hat{\sigma}$ denote the estimates of μ and σ). The experiment was terminated when answers were obtained at these 5 levels. Note that this criterium is dynamic, since $\hat{\mu}$ and $\hat{\sigma}$ will change during the experiment.

The resolution of the sound producing equipment was 1 dB, and during the experiment μ and σ were assumed to be integers. σ was also given the restriction $0 \text{ dB} < \sigma < 11 \text{ dB}$. After termination of each experiment $\hat{\mu}$ and $\hat{\sigma}$ were calculated with an accuracy of 0.1 dB. In order to make it possible to adapt to a time-varying point of equal loudness calculations at any time only included the 10 immediately previous answers. A typical experiment is most easily illustrated by looking at the experimenter's monitor terminal as shown in Figure 3.

2.4 Apparatus

The comparisons between 1 kHz and 63 Hz were carried out in an anechoic chamber, where the sound was produced by 8 13" loudspeakers mounted 2 by 4 in one wall of a box. The loudspeakers were driven by two 120 W amplifiers (Bang & Olufsen, Beolab 5000). The subject was seated in a chair with his head in front of and facing the loudspeakers at a distance of 1.1 m.

The comparisons between 63 Hz and the lower frequencies were carried out in a specially designed test chamber, where 16 electrodynamic loudspeakers produced the sound (13). In this experiment the 5 cubic metre room at the back of the loudspeakers was used instead of the normal 16 cubic metre test chamber, since the smaller volume allowed a higher sound pressure to be obtained.

The systems were calibrated by measuring the sound pressure at the position of the subject's head, but without a subject present (Brüel and Kjaer equipment: microphones 4133/4147, preamplifiers 2619/2619, measuring amplifiers 2606/2607, real time analyzer 2131, pistonphone 4220).

The maximum sound pressure levels that could be obtained are shown in Table 1, together with harmonic distortion and deviations in sound pressure resulting from changes in position.

Table 1.
Properties of the sound field in the anechoic room and the infrasound test chamber. Distortion levels are given relative to the fundamental at maximum sound pressure level and at 10 dB below maximum level. The maximum deviation in sound pressure level given in the last row refers to the range resulting from a ±10 cm change in position up/down, left/right or forward/backward.

		anechoic room		infrasound test chamber					
frequency	Hz	1000	63	63	31.5	16	8	4	2
max. SPL	dB	100	117	125	125	133	133	133	133
2nd harmonic at max. SPL	dB	-53	-26	-41	-33	-44	-42	-36	-35
3rd harmonic at max. SPL	dB	-57	-37	-55	-61	-39	-34	-30	-29
2nd harmonic at 10 dB below max. SPL	dB	-62	-37	-48	-37	-55	-51	-46	-45
3rd harmonic at 10 dB below max. SPL	dB	-58	-53	-59	-64	-60	-55	-47	-44
max. deviation in SPL	dB	1.8	0.7	0.4	0.2	0.1	<0.1	<0.1	<0.1

The presentation of the tones was controlled from an HP 21MX computer by means of two purpose-made attenuators (0 to -120 dB with 1 dB resolution) and two switches that gradually turned the signal on and off within periods of 500 milliseconds. The envelope of the signals is shown in Figure 4. The computer also recorded the answers, made the calculations, and presented the course of the experiment on the monitor terminal.

2.5 Experimental design
As values at 63 Hz served as references for the lower frequencies, comparisons between 1 kHz and 63 Hz were carried out at the beginning of the experiment, and for each subject mean values of two determinations were used. The order in which the subjects received the lower frequencies (2, 4, 8, 16 and 31.5 Hz) was determined from a latin square design that balanced out both order and carry-over effects (14). Within each frequency a similar design was used to determine the order in which the subjects received the five loudness levels (20, 40, 60, 80 and 100 phon).

2.6 Procedure
In each experimental session two subjects were tested by turns for periods of approximately 10 minutes (the time to finish one frequency at 5 loudness levels). The duration of a session was around 3.5 hours, including calibration before each new frequency.

In a written instruction the subjects were asked to listen to the tone-pairs and after each pair indicate by pressing a button, which one he perceived as loudest, the first or the second tone. The meaning of "loudness" was explained as the quality that is altered by the volume control of a radio receiver. In order to make them familiar with the experimental procedure all subjects went through an experiment at 60 phon, before any results were used.

After the experiments the subjects answered a questionnaire. In the answers they expressed a general contentment with the conditions of the experiment (test rooms, duration of the tones and pauses, duration of the experiment). The questions also concerned the difficulty in comparing the tones and the possible annoyance from the tones. Answers to these questions will be reported in section 3.

3. RESULTS

Usually a point of equal loudness was determined after 8-10 tone-pairs. In a few cases large inconsistency in the answers or a time-variation of the point of equal loudness made up to 20 presentations necessary.

At the highest loudness levels some subjects had equal loudness points above the dynamic range of the sound producing systems, and no values could be determined. At points where a value exists for all subjects, simple statistics is used, and in case of missing values the procedure for a censored normal distribution is used (15). Any point where more than 50% are missing is omitted. Results are given in tabular form (Table 2) and as curves of equal loudness (Figure 5).

Table 2.
Points of equal loudness in the frequency range 2-63 Hz.

loudness level	frequency	mean value	standard deviation	number of subjects	s.e. of mean
phon	Hz	dB	dB		dB
20	63	58.0	6.6	20	1.5
20	31.5	75.1	6.5	20	1.5
20	16	95.1	5.8	20	1.3
20	8	109.4	5.9	20	1.3
20	4	120.7	5.2	20	1.2
20	2	127.6	3.5	20	0.8
40	63	71.7	6.1	20	1.4
40	31.5	83.4	7.3	20	1.6
40	16	101.3	8.4	20	1.9
40	8	114.3	6.4	20	1.4
40	4	124.8	5.7	19	1.3
40	2	129.7	4.1	16	0.9
60	63	82.8	4.8	20	1.1
60	31.5	90.9	7.4	20	1.7
60	16	106.9	7.8	20	1.7
60	8	118.1	6.6	20	1.5
60	4	127.4	5.5	18	1.3
60	2	132.6	5.0	11	1.3
80	63	95.6	4.3	20	1.0
80	31.5	102.5	9.0	20	2.0
80	16	116.5	8.6	19	1.9
80	8	125.6	8.6	18	2.0
80	4	132.6	6.3	10	1.7
100	63	112.3	3.7	20	0.8
100	31.5	119.5	7.3	16	1.7
100	16	128.4	7.8	15	1.8

The overall mean of $\hat{\sigma}$ was 1.38 dB, and in 49% of the cases, completely consistent answers were given, leading to a $\hat{\sigma}$ of 0.1 (lowest possible value).

In the answers to the questionnaire 75% of the subjects indicated that they found the comparisons "difficult", 25% "reasonably easy" and 0% "easy". 40% indicated that they would prefer to hear the tone-pairs more than once before answering. The subjects were also asked, whether they found some of the tones annoying. 35% indicated "yes, very", 60% "yes, somewhat", and 5% "not at all". The complaints concerned pressure in the ear, large and sometimes painful movements of the eardrum, tickling in the ear, and the like.

4. DISCUSSION

From Figure 5 it can be seen that the loudness curves run almost parallel in the infrasound region, and much closer than in the audio region. For example, the distance between the 20 and the 80 phon curves has decreased from 60 dB at 1 kHz to approximately 16 dB at 8 Hz. Consequently, infrasound only a few dB above the hearing threshold will seem loud and possibly annoying. It is also possible to explain the fact that a small change in the infrasound content of a complex sound may change the loudness of the sound considerably.

In order to demonstrate to what extent the results are in agreement with existing knowledge about the hearing at low frequencies, the following three sections show comparisons with 1) the threshold curve, 2) existing loudness curves for infrasonic frequencies, 3) ISO/R 226 equal loudness curves.

4.1 Threshold curve

Figure 5 also includes a threshold curve based on a weighted mean of 4 recent studies. The threshold curve and the loudness curves complement each other remarkably well. The shape of the threshold curve is very close to that of our 20 phon curve, and the curve is positioned just below that at a distance close to the distance between the loudness curves.

4.2 Existing loudness curves for infrasonic frequencies

Whittle et al. have given curves of equal loudness in the frequency range 3.15-50 Hz. The frequencies used were not the standardized octave frequencies, so a direct point to point comparison is not possible. Figure 6 shows the results together with the results of the present study. The agreement between the two sets of curves is very good with respect to shape and slope.

There is a minor disagreement at the lowest frequencies where the curves of Whittle et al. seem to keep their slope, while ours become less steep. This may be caused by the gating of the signal (Figure 4), which changes the spectrum from the line spectrum of a pure tone to a continous spectrum centered around the tone. This effect is dependent on the duration of the tones and the rise and decay times, and it is most prominent at the lowest frequencies. Whittle et al. did not report the exact envelope of their signals. The significance of the gating effect will be investigated in a later experiment.

Whittle et al. did not make comparisons with 1 kHz, so a direct labelling of their curves with phon values was not possible. Instead of that they used the ISO/R 226 curves to find the loudness level of their 50 Hz reference tones, and the curves were labelled with the values: 33.5, 53 and 70 phon. As it will be seen in section 4.3, there are discrepancies between the ISO curves and those of the present study, and of course, this leads to a disagreement in the labelling of our curves and those of Whittle et al. Their lowest curve is for example labelled 33.5 phon, although it is below our 20 phon curve in almost the entire frequency range.

4.3 ISO/R 226 equal loudness curves
The frequencies 31.5 and 63 Hz are already covered by the ISO/R 226 loudness curves (16). A comparison with those is shown in Table 3. The present values are generally higher than those of ISO, the difference being statistically significant at most points.

Table 3.
A comparison between ISO/R 226 and results from the present study at 63 and 31.5 Hz.

freq. Hz	loudness level phon	ISO/R 226 dB	present study dB	s.e. of mean dB	t	sign. level
63	20	45.7	58.0	1.5	8.2	0.001
63	40	59.5	71.7	1.4	8.7	0.001
63	60	74.3	82.8	1.1	7.7	0.001
63	80	90.4	95.6	1.0	5.2	0.001
63	100	107.9	112.3	0.8	5.6	0.001
31.5	20	64.3	75.1	1.5	7.2	0.001
31.5	40	75.4	83.4	1.6	5.0	0.001
31.5	60	87.6	90.9	1.7	1.9	0.1
31.5	80	101.3	102.5	2.0	0.6	n.s.
31.5	100	116.6	119.5	1.7	1.7	n.s.

Two conditions of ISO/R 226 have not been fulfilled in this study: 1) Mean values were reported instead of modal values. Mean values were chosen, since 20 observations were considered too few to determine the distribution accurately enough to find the modal values. The distributions did not show any obvious skewness, and the mean and the modal values are equal, if the distribution is assumed to be normal. 2) The sound field was only approximately a free progressive plane wave. The changes in sound pressure level for changes in position given in Table 1 illustrate the deviations from a plane wave. The deviations are small and cannot explain differences as great as 12.6 dB.

At present we are not able to explain the disagreement between our curves and those of ISO/R 226. A similar discrepancy exists between the ISO/R 226 threshold curve and the curve based on the 4 recent investigations, as can be seen in Figure 7.

4.4 Difficulties in the comparisons
In the answers to the questionnaire the subjects reported

difficulties in comparing the tones, especially when the frequencies were far from each other. Nevertheless, the low values of $\hat{\sigma}$ show that the answers were in general very consistent, and in spite of the subjects' own scruples the results seem very reliable.

4.5 Annoyance

The annoyance indicated in the answers to the questionnaire is not surprising, since tones louder than 100 phon were included. It is not possible to attach the annoyance to specific frequencies and levels. Whether the annoyance of infrasound is related to the loudness sensation is not known at present, and a projected experiment deals with determination of equal annoyance contours at low and infrasonic frequencies.

5. CONCLUSION

A set of equal loudness contours for low and infrasonic frequencies have been determined. The contours complement very well existing knowledge about the hearing at infrasonic frequencies, although there are minor but statistically significant disagreements with the low-frequency part of the ISO/R 226 loudness curves. Some uncertainty is also attached to the exact values at 2 Hz.

It is obvious that existing curves like the A curve cannot be used to measure loudness of sounds containing infrasound, unless they are given an appropriate extension down to 2 Hz or lower. It is also obvious that a single curve to be used at all loudness levels cannot be developed, since different relative weighting of high and low frequencies is required at different loudness levels. This phenomenon is also known from the audio region, and it has led to the development of the three weighting curves A, B, and C. However, the effect becomes even more prominent, when the infrasonic range is included.

As the loudness curves run almost parallel in the infrasonic region, it may be possible to develope a weighting curve suitable for measuring loudness of infrasound. The curve should be restricted in frequency and thus not provide any large overlapping into the audio region, and users should be aware of the steep rise in loudness with an increase in sound pressure above the hearing threshold.

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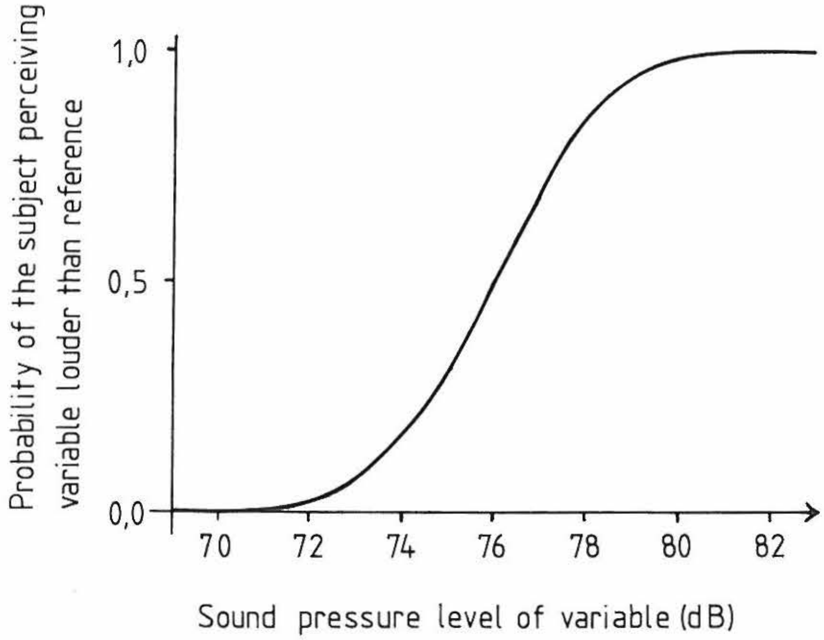


Figure 1.
Psychometric function for a given subject, and for fixed values of reference frequency, reference level and variable frequency. In this case, μ=76.0 dB and σ=2.0 dB.

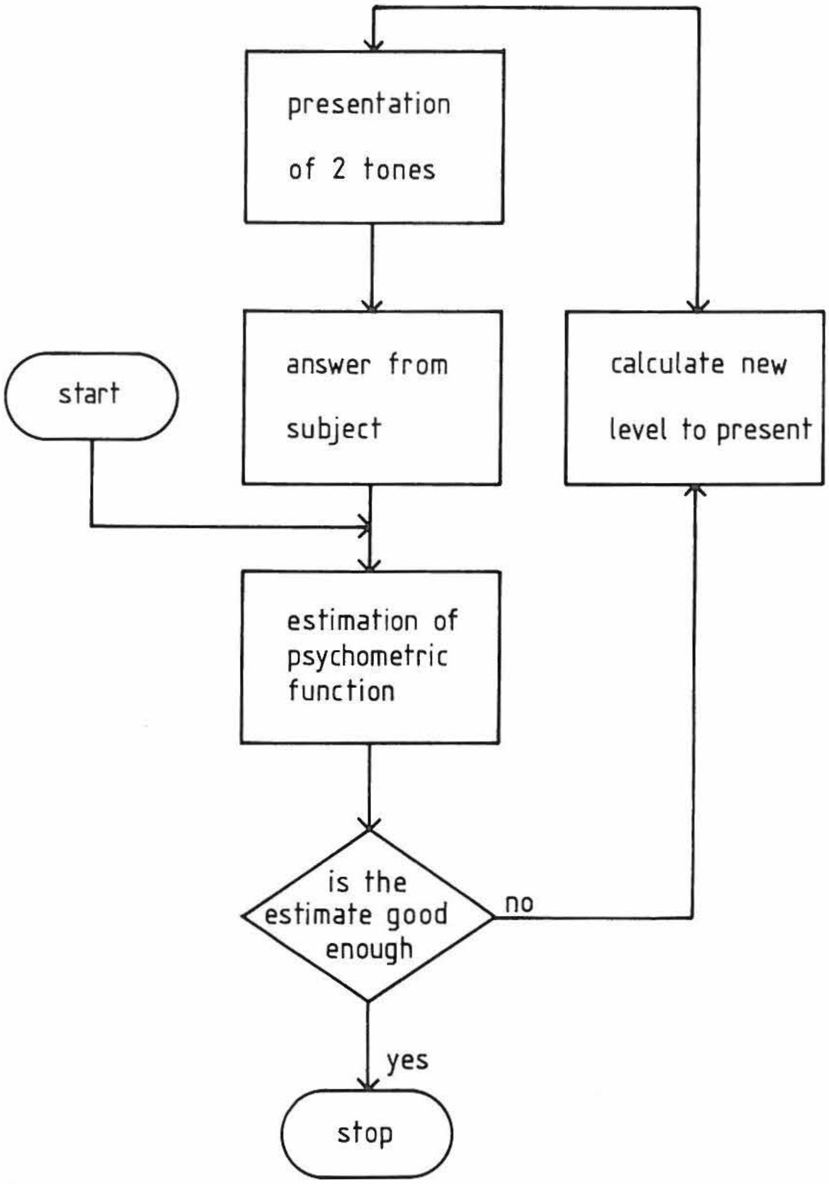


Figure 2.
Flow chart of the psychometric method.

REFERENCE FREQUENCY: 1000 HZ, VARIABLE FREQUENCY: 63 HZ,
LOUDNESS LEVEL: 60 PHON, REFERENCE LEVEL: 60 DB.

```
80 I   >
   I
   I       - >
   I       *    >
   I    -  -  -  -       >
75 I    *     *  *     -  - >
   I    -     -  - >-  *  *  -  -
   I      <         *  -  -  *  *
   I                - <      -  -
   I                           <
70 I<-+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+-->
   I                           10                            20
   I
   I
   I
65 I
   I
   I
   I
   I
60 I
```

Figure 3.
Typical experiment as seen by the experimenter on the monitor terminal. The horizontal axis is a time-axis showing presentation number from 1 to 20. The vertical axis shows the sound pressure level. Presented levels and associated answers are indicated by >: "variable is louder than reference", and <: "variable is softer than reference". * shows the running value of $\hat{\mu}$, and $\hat{\mu}-\hat{\sigma}$ and $\hat{\mu}+\hat{\sigma}$ are shown with -. The first presentation was at 70 dB, which was perceived "softer" than the reference (<). For the second presentation the level was increased by 10 dB to 80 dB, and the answer was now "louder" (>). After this answer the maximum-likelihood estimation gave $\hat{\mu}$=75 dB, $\hat{\sigma}$=1 dB. Then $\hat{\mu}-2\hat{\sigma}$=73 dB was selected for the third presentation, the answer "softer" was obtained, and new estimates were $\hat{\mu}$=77 dB, $\hat{\sigma}$=1 dB. The fourth presentation was at $\hat{\mu}+\hat{\sigma}$=78 dB, the answer was "louder", and new estimates were $\hat{\mu}$=75 dB, $\hat{\sigma}$=1 dB, etc. etc. After the 10th presentation $\hat{\mu}$=73 dB and $\hat{\sigma}$=1 dB; 71, 72, 73, 74 and 75 dB had all been presented, and the experiment was terminated.

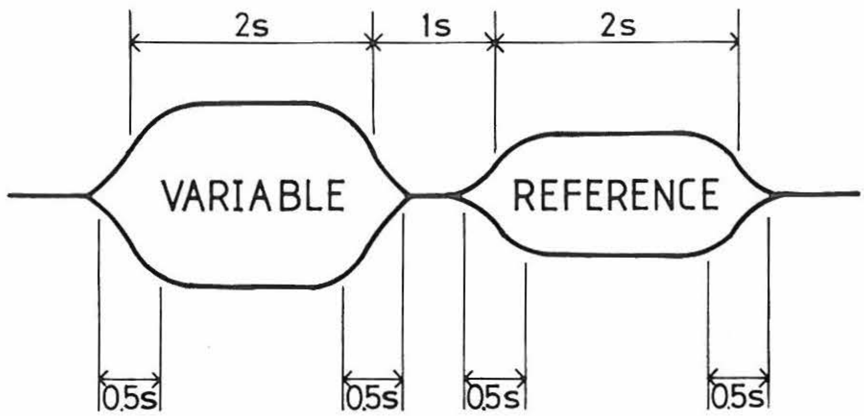


Figure 4.
Envelope of the test tones.

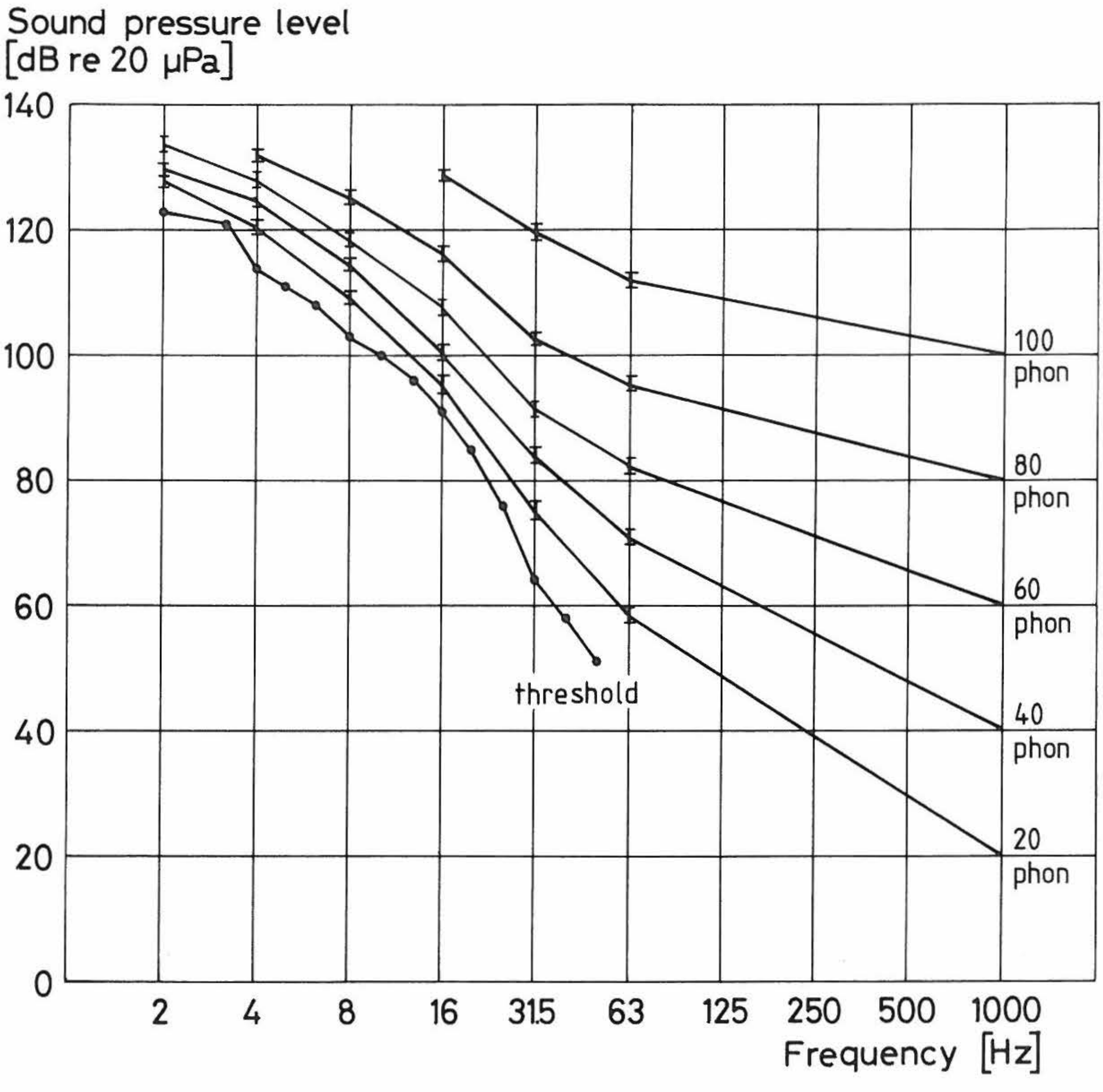


Figure 5.
Curves of equal loudness. Vertical bars indicate ±1 standard error of mean. The threshold curve is based on four recent studies: Whittle et. al. (5), Table 3 "continous" column; Yeowart et al. (6), Table 3 converted to binaural hearing by subtraction of 3 dB; Yeowart et al. (7), Table IV; Yeowart et al. (7), Table VI. A few interpolations had to be made to convert to the standardized one-third-octave frequencies.

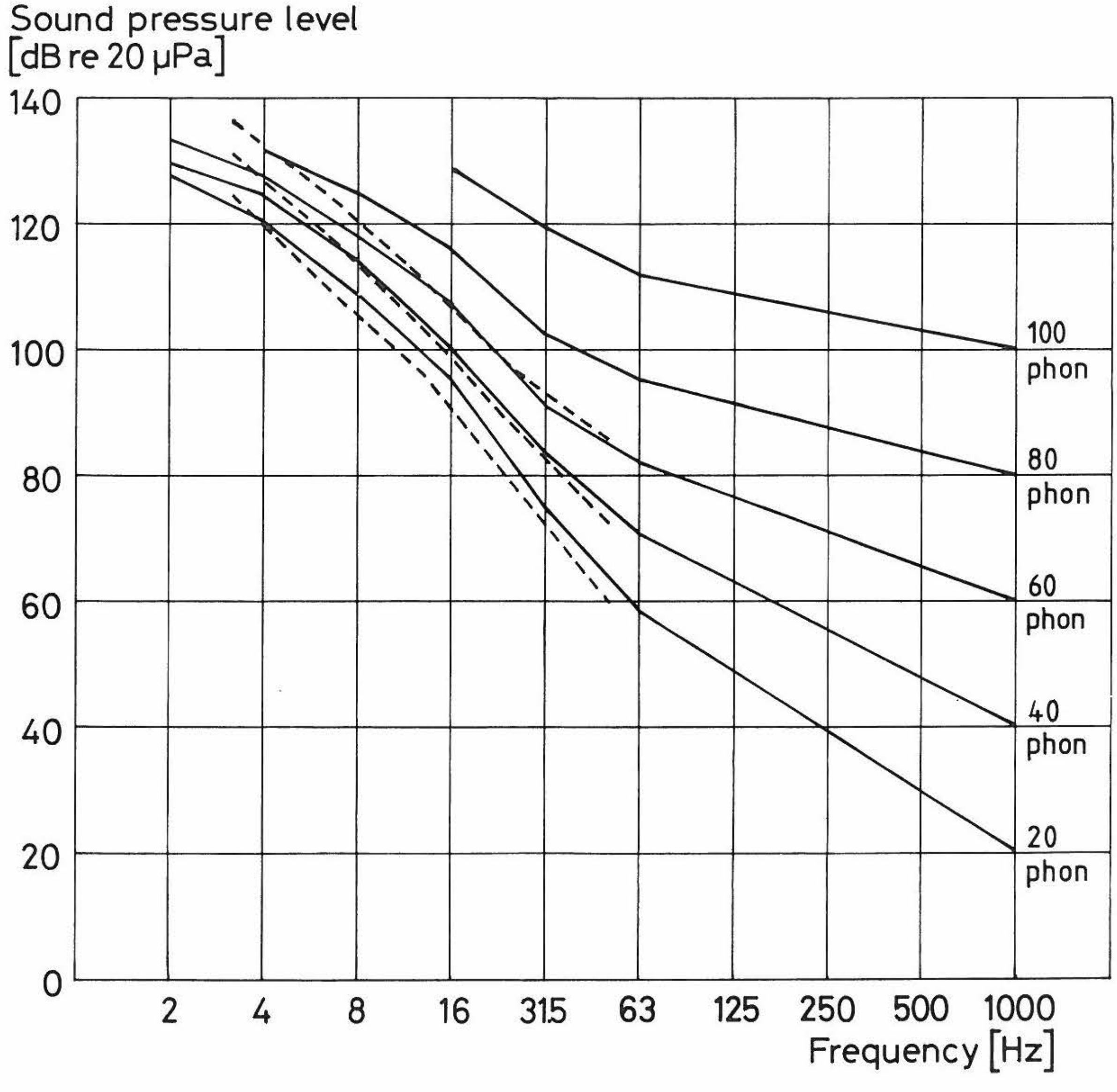


Figure 6.
Comparison between equal loudness curves of Whittle et al. (5) (dotted lines) and the present study.

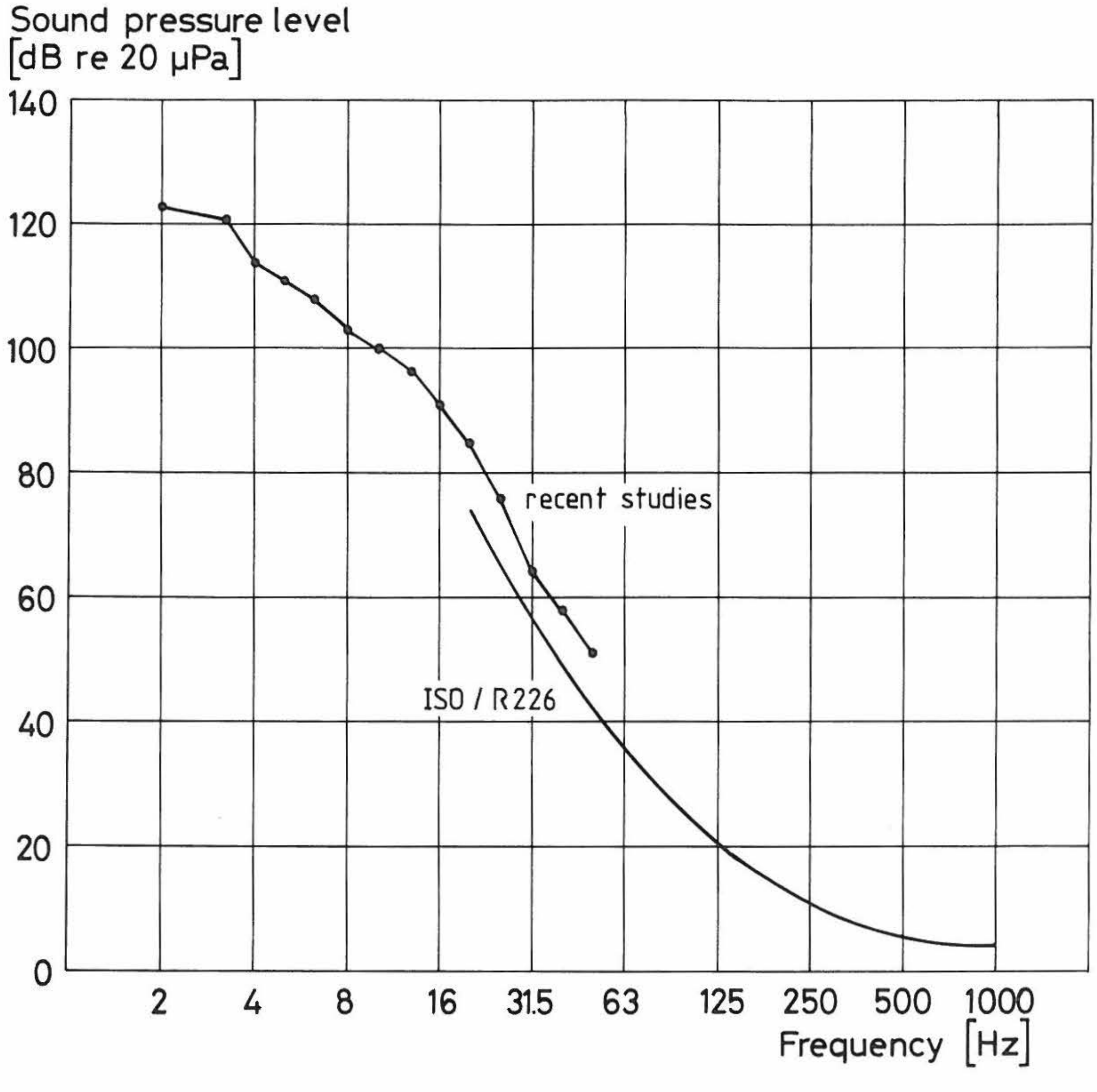
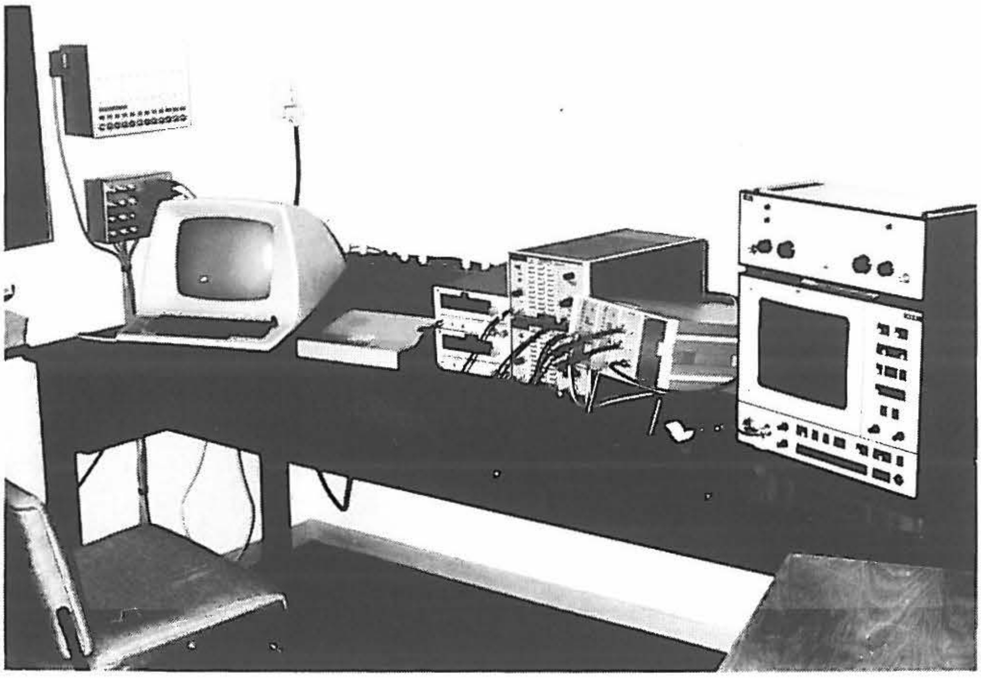
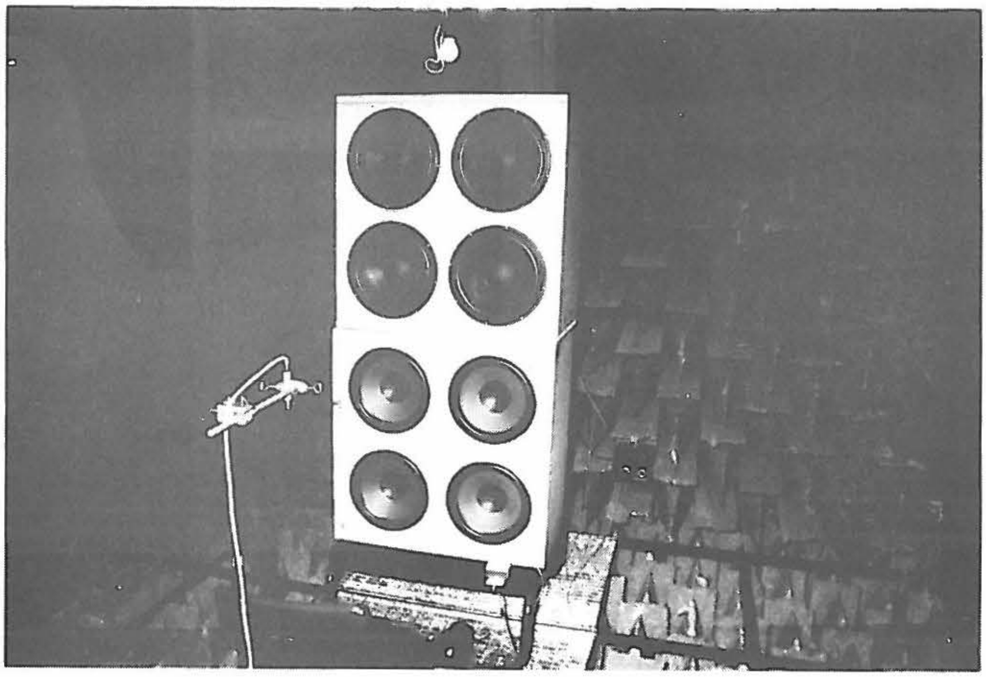
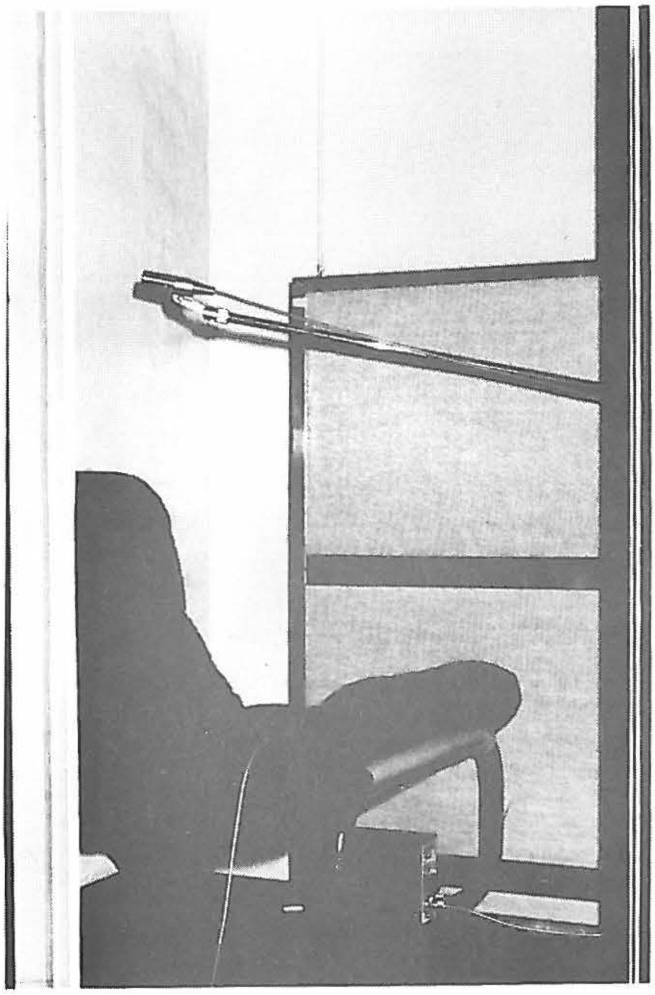


Figure 7.
Comparison of threshold values from ISO/R 226 and from four recent studies (see Figure 5).



The electronic equipment used to generate and control the sound. The computer is in an adjacent room.





Measurement of the sound field in the anechoic room (above) and the infrasound test chamber (left)

A subject under test in the anechoic room (above) and the infrasound test chamber (left)

Paper D

Equal annoyance contours for infrasonic frequencies

EQUAL ANNOYANCE CONTOURS FOR INFRASONIC FREQUENCIES

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ABSTRACT

Eighteen subjects (age range: 18-25) rated the annoyance of 18 sound stimuli on a graphic scale (four infrasonic frequencies at different intensity levels and four levels of a 1000 Hz octave-filtered pink noise for reference). The exposure time for each stimulus was 15 minutes. The order of exposures was determined from a latin square and each subject was exposed to only one stimulus a day. Equal annoyance contours were constructed to connect points that caused the same annoyance rating.

The equal annoyance curves demonstrate that the lower the frequency the greater must be the sound pressure to cause a given amount of annoyance. Compared with 1000 Hz the curves lie much closer in the infrasonic range. The closeness of the curves in the infrasonic region implies that relatively small changes in sound pressure may cause large changes in annoyance.

Based on the experimental results a weighting curve with a slope of 12 dB per octave is suggested for assesment of annoyance and loudness in the infrasonic range. A curve with the same slope and an attenuation of 0 dB at 10 Hz is at present under consideration in the International Standardization Organization. For environmental purposes a maximum permitted level of 95 dB is proposed to be used with this curve.

1. INTRODUCTION

Infrasound, at pressure levels that can be heard, is quite common in our daily surroundings, and may cause considerable annoyance. A few countries have introduced measurement procedures and hygienic limits, but there has been a deplorable lack of experimental facts on which to base these.

For audiosound the agreement between annoyance and loudness is usually so good that dB(A) and similar measures developed from loudness investigations can be used as an estimate of the annoyance effect. It might therefore seem a possibility to use the equal loudness curves already described for the infrasound region (1, 2, 3, 4) as a base for an extension downward of existing weighting curves. However, the close relation between annoyance and loudness found at higher frequencies may not exist in the infrasound region, because very low frequencies are perceived as a throbbing sound instead of a tone, and this may have an influence on the annoyance experience. Several investigations (5, 6, 7, 8, 9, 10) seem to indicate that the assumed agreement between loudness and annoyance already becomes questionable in the low frequency range 20-100 Hz.

The aim of the present project has therefore been to establish equal annoyance contours in the frequency range 4-31.5 Hz that may be used to determine hygienic limits.

2. METHOD

2.1 Subjects

Eighteen engineering students participated (15 men and 3 women; age range: 20-25). All were paid volunteers, and all were familiar with infrasound stimuli from their participation in our work on equal loudness curves for the infrasonic range. An audiometric test ensured normal hearing.

2.2 Sound conditions

To simplify matters - in our present state of ignorance - we have used only pure tones as stimuli and have - for reference - also included a 1000 Hz octave-filtered pink noise. To make comparisons possible we decided to use the same frequencies as in our work on equal loudness. Based on results from the loudness investigation four intensity levels that ensured a satisfactory dynamic range for each frequency were chosen. Because it was not possible to achieve a sufficiently high sound pressure in the test room, we were, however, not able to test reactions to 2 Hz, and for the same reason 4 Hz was only presented at two levels. The 18 stimuli used are shown in Table 1.

2.3 Apparatus

The experiments were performed in a 16 cubic metre pressure chamber (11). We took some pains to approach the experimental situation to a living room situation, so the test room was fitted with a carpet, cosy lamps and an easy-chair for the subject. The infrasound was emitted via 16 electrodynamic loudspeakers driven by a B & K 2712 power amplifier. The loudspeakers were concealed in the wall behind a screen. The 1000 Hz noise was emitted via an equalized Hi-Fi sound reproduction system with the loudspeaker placed 140 cm from the subject. The sound pressure levels given in Table 1 are levels measured before the experiment at the point where the subjects head would be during the experiment. An HP 21MX computer controlled the experimental session.

The subjects indicated degree of annoyance experienced on a 150 mm long graphic scale. The left end was marked "not at all annoying" and the right end "very annoying" (see Figure 1). This type of scale has a number of advantages. It leaves the subject greater freedom of discrimination, the problems of interpretation of verbally graduated scales are eliminated, and it is easy to administer.

2.4 Experimental design

Each subject was exposed to the whole range of stimuli. To balance out possible carry-over effects the order of exposures for each subject was determined from a special sort of an 18 x 18 latin square that ensured that no stimulus was preceded by any other stimulus more than once (12). Each subject was exposed to only one stimulus a day for 18 days and at the same hour every day.

2.5 Procedure
The subjects received a written instruction with a description of the experimental procedure. A session lasted 20 minutes. During this period the subject was alone in the test chamber. He was supplied with two newspapers and instructed to read till the end of the session. After five minutes of silence the sound stimulus was presented for 15 minutes, and then, after a delay of 15 seconds, the subject was asked via an intercom to indicate degree of annoyance experienced on the graphic scale (Question 1). In the instruction the subject was requested to accept the "not at all annoying" label as descriptive of his situation during the five minutes of silence and to indicate degree of annoyance during sound exposure in accordance with this definition.

After a further delay of 20 seconds the subject was asked to indicate on the same scale the degree of annoyance that he would probably feel at home, if his neighbour produced the same sound for two hours (Question 2).

One minute after the sound exposure was stopped, the subject was requested to adjust the sound of a 1000 Hz octave-filtered pink noise so that it was perceived as equally annoying as the sound heard while reading. This task was primarily incorporated for methodological reasons, and the results will not be discussed in this paper.

When the subjects had been exposed to the series of sound stimuli, they were asked to indicate on the graphic scale where they would place the label "unacceptable annoyance" if the label referred to noise in their home environment (Question 3).

After the termination of each experimental setting the subjects were allowed - in writing - to comment freely on the stimulus situation.

3. RESULTS

3.1 Question 1 and 2

Degree of annoyance was measured in mm, and means and standard deviations for each of the 18 stimuli are presented in Table 1.

Table 1. Means and standard deviations for Question 1 (Annoyance during experiment) and Question 2 (Imagined annoyance at home).

Stimulus		Question 1		Question 2	
Frequency (Hz)	SPL (dB)	Mean[a] (mm)	SD (mm)	Mean[a] (mm)	SD (mm)
1000	20	6	7	11	13
	40	25	20	38	26
	60	54	36	71	36
	80	115	33	126	27
31.5	75	17	22	24	33
	84	39	37	56	50
	93	67	37	85	37
	102	93	39	109	33
16	95	21	29	24	31
	102	56	47	65	49
	109	80	38	97	40
	116	114	33	128	27
8	109	34	33	49	46
	114	61	41	69	41
	119	88	41	1o2	38
	124	102	40	118	29
4	120	24	28	36	46
	124	68	43	83	48

[a] n = 18 for each mean

The main difference between results from the two questions is that most of our subjects would find the same sound more annoying if heard at home. For both questions the relationship between sound pressure level and annoyance rating is linear for the infrasonic frequencies. The coefficients of correlation for 31.5, 16, 8 and 4 Hz were respectively: 0.999, 0.998, 0.991, and 1.000 (Question 1) and 0.998, 0.998, 0.991, and 1.000 (Question 2). Means for Question 2 are presented graphically in Figure 2 together with the regression lines for the infrasonic frequencies.

Equal annoyance points have been determined in the following way: It is assumed that the relation between sound pressure level and degree of annoyance for a given infrasonic frequency is expressed by the equation for the regression line: $y = \hat{\alpha} + \hat{\beta}(x - x_0)$, which gives

$$x = \frac{y - \hat{\alpha}}{\hat{\beta}} + x_0 \qquad (1)$$

where y is the annoyance in mm, x the corresponding sound pressure level, x_0 the mean of the sound pressure levels used at a given frequency, $\hat{\alpha}$ the mean annoyance for that frequency, and $\hat{\beta}$ the slope of the regression line for that frequency. In order to obtain dB values for equal annoyance points, the mean annoyance found for 1000 Hz at 20, 40, 60, and 80 dB respectively has been inserted in (1) as y.

The inaccuracy of the estimate of the dB values for a given equal annoyance point is a function of the inaccuracy of the observed annoyance value for 1000 Hz and of $\hat{\alpha}$ and $\hat{\beta}$ (x_0 is a constant). The variance for annoyance values at 1000 Hz were calculated from the observations, and estimates of the variances for $\hat{\alpha}$ and $\hat{\beta}$ were obtained from the regression analysis; thus through linearization of (1) as a function of y, $\hat{\alpha}$ and $\hat{\beta}$ an approximate estimate of the SD of the dB values can be calculated from the following equation:

$$\delta(x) = \sqrt{\frac{\delta^2(y) + \delta^2(\hat{\alpha}) + \delta^2(\hat{\beta})\,(x - x_0)^2}{\hat{\beta}^2}} \qquad (2)$$

Means and standard deviation of equal annoyance points calculated for Question 1 as well as for Question 2 are shown in Table 2.

Table 2. Mean sound pressure levels in dB (and their standard deviations) for equal annoyance points in the infrasonic range calculated for Question 1 and for Question 2 with 1000 Hz as reference frequency.

Question	Frequency (Hz)	Reference SPL (dB) 20	40	60	80
1	31.5	71.5 (2.8)	78.4 (2.6)	88.5 (3.3)	109.7 (4.3)
	16	91.2 (2.1)	95.7 (1.9)	102.4 (2.3)	116.4 (2.5)
	8	102.3 (2.7)	106.5 (2.3)	112.8 (2.2)	125.9 (2.6)
	4	118.4 (1.1)	120.2 (0.9)	122.8 (1.0)	128.2 (1.9)
2	31.5	70.3 (3.1)	78.9 (2.8)	89.4 (3.0)	106.9 (3.6)
	16	91.8 (1.9)	97.2 (1.8)	104.0 (1.9)	115.2 (1.9)
	8	101.2 (2.8)	106.8 (2.3)	113.7 (2.0)	125.1 (2.2)
	4	117.9 (1.6)	120.2 (1.1)	123.0 (1.0)	127.7 (2.1)

The resulting equal annoyance contours shown in Figure 3 are determined from answers to Question 2 (imagined annoyance at home), because this question bears a closer resemblance to the task required in similar studies concerned with the annoyance effect of audiosound. As can be seen from Table 2, the differences between pairs of equal annoyance points from the two questions are small and unsystematic and therefore ignorable.

The equal annoyance curves demonstrate the not very surprising fact that the lower the frequency the greater must be the sound pressure to cause a given amount of annoyance. Compared with 1000 Hz the curves lie much closer in the infrasonic range. This change is already seen at 31.5 Hz, but becomes even more pronounced with decreasing frequency.

3.2 Question 3

The mean score for Question 3 (unacceptable annoyance) for the 18 subjects was: 5o mm. For each frequency the sound pressure levels that correspond to a 50 mm degree of annoyance were calculated from equation (1). The maximum sound pressure that our subjects would tolerate in home surroundings is 83 dB at 31.5 Hz, 100 dB at 16 Hz, 109 dB at 8 Hz, and 121 dB at 4 Hz. The means are presented graphically in Figure 5.

3.3 Comments

Information extracted from the comments must be taken with caution as this was a nonobligatory task. Some general trends emerged though and seem worth mentioning: Exposure to infrasound gave - in contrast to the 1000 Hz noise - rise to physiological complaints like pressure in the ears, at the eardrum or in the head - headache or a tendency to headache - and interference with breathing. Other complaints that were often mentioned are vibrations of clothes and newspapers, and changes in the perception of the sound caused by body movements or movements of the newspaper.

The comments also reflected that there were large individuel differences as to how easily the subjects adapted to the sound exposures.

4. DISCUSSION

The closeness of the curves in the infrasonic region implies that relatively small changes in sound pressure may cause large changes in annoyance. From an environmental point of view this is important because a modest reduction in sound pressure will in some cases be enough to alleviate annoyance caused by infrasonic noise. It also means that accuracy is crucial when measuring infrasound, and that specific demands must be made on the measuring equipment.

Several investigations (5, 6, 7, 8, 9, 10) have shown that dB(A) values are unsatisfactory for assessment of annoyance from sounds containing a considerable amount of low frequency energy. It has been found that: 1) Very annoying sounds sometimes had rather low dB(A) values and 2) Sounds that differed only slightly when measured with the A-curve often were far apart in annoyance rating. The disagreement between dB(A) values and experience of annoyance is a consequence of the level-dependent slopes of the annoyance curves in the low frequency region and the closeness of the curves at the lowest frequencies. The following two examples illustrate the problem: 1) A 112 dB 20 Hz tone is rated as annoying as an 80 dB noise band at 1000 Hz (see Figure 3) although the sound level is as low as 62 dB(A). 2) Two 20 Hz tones with dB(A) values of 41 and 49 will have sound pressure levels of 91 and 99. From Figure 3 it can be seen that these two tones will lie on two different annoyance curves and that the difference in annoyance will be as large as the difference between 40 and 60 dB at 1000 Hz.

4.1 Comparison with equal loudness curves

The disagreement between dB(A) values and ratings of annoyance has often been interpreted as a difference between the experience of loudness and the experience of annoyance. In Figure 4 the equal loudness curves described by us (3, 4) are shown together with the equal annoyance curves. The two sets of curves are remarkably similar in their general shape, especially when one considers that they have been established by two very different methods, and that the number of subjects used in the two studies is rather small. Thus the relation between loudness and annoyance found at higher frequencies seems to hold for the low and infrasonic regions too, and the explanation of the disagreement between dB(A) values and annoyance ratings could equally well have been given on the basis of the shape of the loudness curves.

It should be mentioned that although the two sets of curves are similar in shape the annoyance curves lie slightly lower than the loudness curves; a preliminary statistical analysis seems to indicate that this difference is significant; a more thorough analysis will, however, be published later.

4.2 Weighting curves

For practical applications it would be convenient, if one weighting curve could cover both the audio and the infrasonic range. However, the fact that the annoyance and the loudness curves show a decreasing steepness in the low frequency region with increasing level implies that a number of curves with different relative weighting of medium, low and infrasonic frequencies would be neccessary.

As the slopes of the equal loudness and equal annoyance curves are reasonable independent of the sound pressure level within the infrasonic range, a single weighting curve for this frequency region would be a better solution (possibly covering a part of the lowest audio frequencies too).

The Technical Committee 43 of the International Standardization Organization is considering a proposal for procedures to be used when measuring noise in the infrasonic range (13). The proposal comprises two weighting curves with different slopes, namely 6 dB per octave (N-weighting) and 12 dB per octave (P-weighting). The mean slopes found in our investigation were 12.3 dB per octave for the loudness curves (2-31.5 Hz) and 11.7 dB per octave for the annoyance curves (4-31.5 Hz). It is clear that the curve with a slope of 12 dB per octave will give the best estimates of loudness or annoyance.

4.3 Hygienic limit

The results discussed so far only refer to the relative annoyance experienced when exposed to certain stimuli, but give no information as to acceptable exposure levels in real life. Question 3 (unacceptable annoyance) was designed to obtain information about this, and it would be interesting to use the ISO 12 dB per octave weighting curve in connection with the results obtained from this question. The ISO curve would have an attenuation of 0 dB at 10 Hz, and if the levels given in Figure 5 are measured with the P-curve, a value around 105 dB will result. However, the means here reported, camouflage the great individual differences in sensitivity to infrasound, and a limit based on means will in many cases be too high. A better criterion would probably be around 95 dB(P). The dashed line in Figure 5 connects points that will give values of 95 dB when measured with the P-curve.

5. PROJECTED EXPERIMENTS

Because so little is known about annoyance caused by infrasound this study has been very limited in scope i.e. only pure tones have been used as stimuli and only young students as subjects. To extend the validity of the reported results it is neccessary to use non-sinusoidal infrasounds as stimuli and to use older persons and different occupational groups as subjects. Outside the laboratory infrasound frequently occurs at places of work and is normally mixed with higher frequencies, thus it has also been planned to study the effect of infrasound on certain performance tasks and investigate reactions to various combinations of infrasound and audiosound.

ACKNOWLEDGEMENTS

This research was financed by Aalborg University and the Danish Council for Scientific and Industrial Research.

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Figure 1. The graphic scale used by the subjects to indicate degree of annoyance.

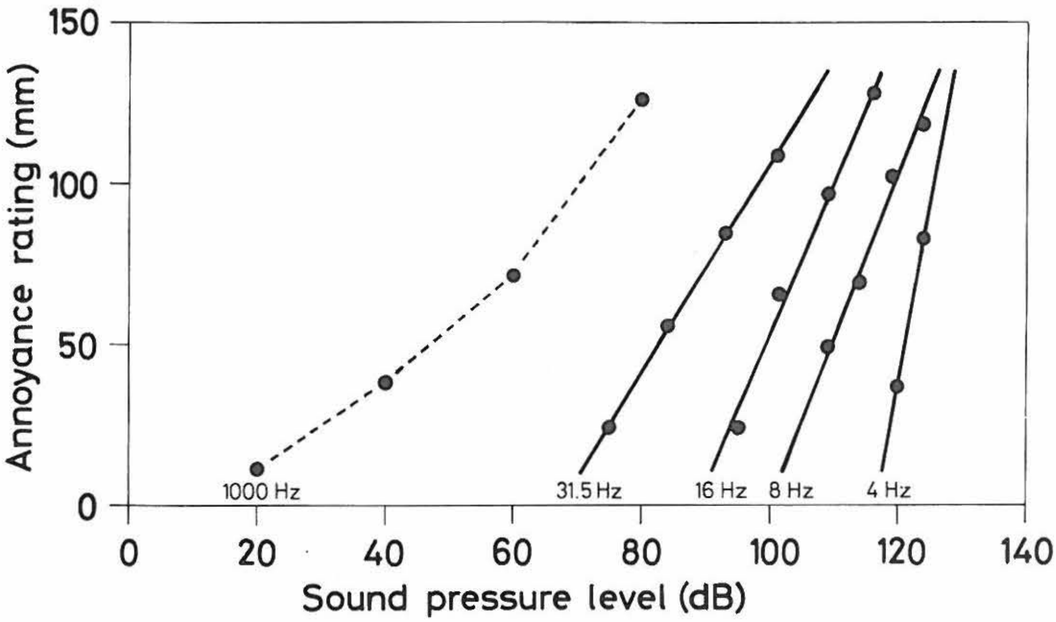

Figure 2. Relation between sound pressure level and annoyance rating (Question 2: Imagined annoyance at home). The filled circles represent the means for each stimulus, and the lines are regression lines for each infrasonic frequency.

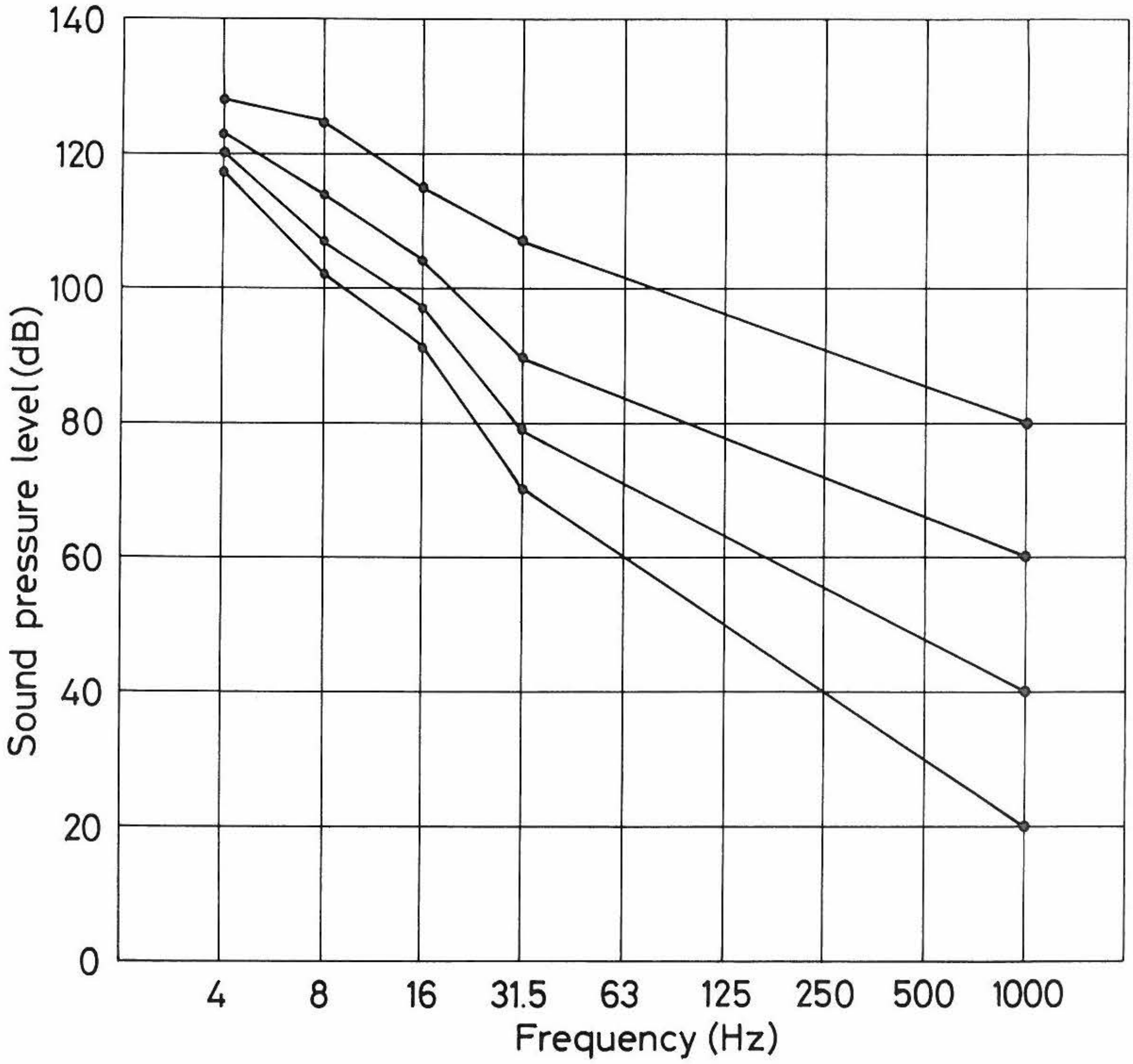

Figure 3. Equal annoyance contours based on results from Question 2 (Imagined annoyance at home).

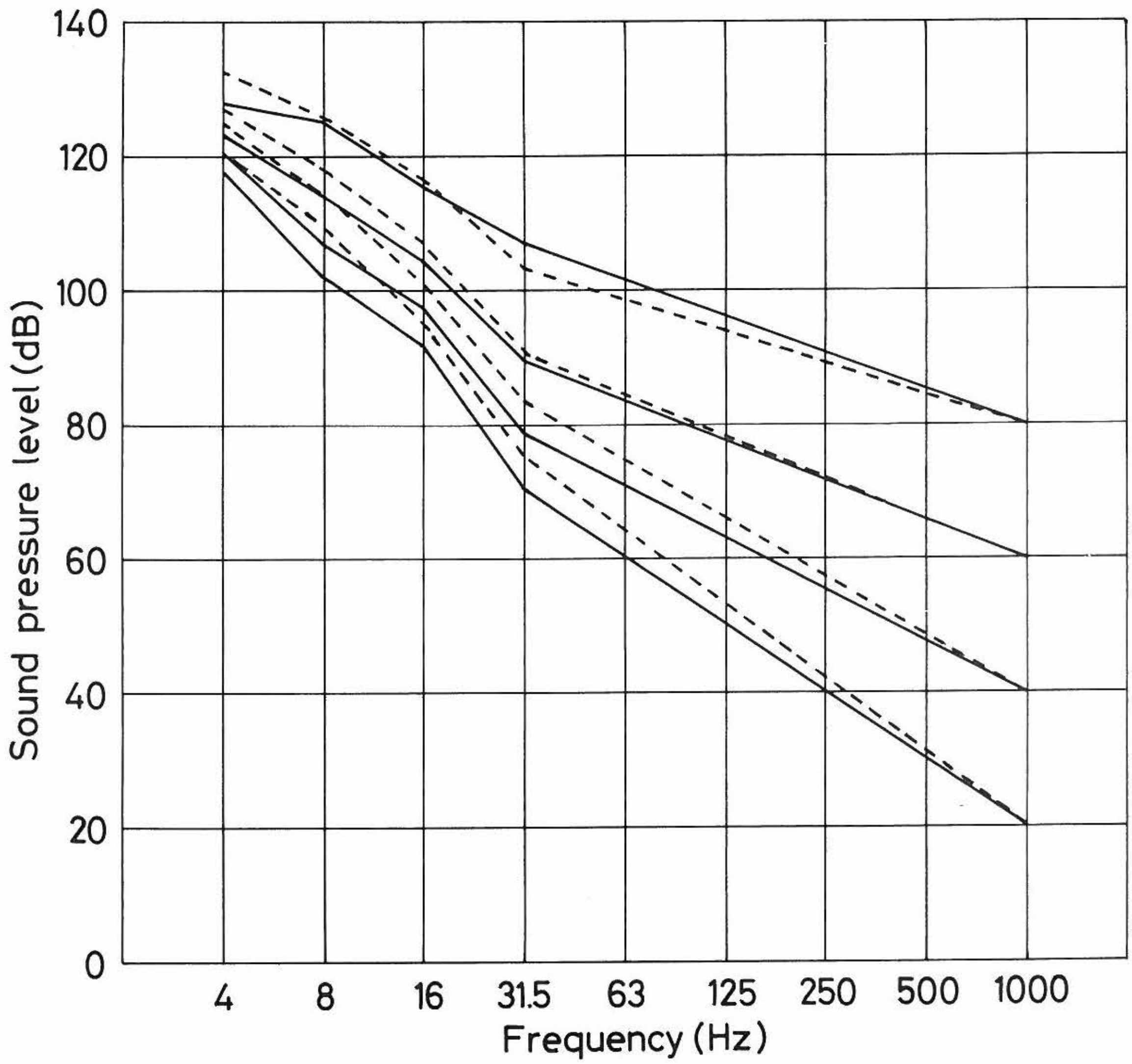

Figure 4. Comparison of equal loudness contours from Møller and Andresen (3, 4) (dashed) and the equal annoyance contours found in this investigation. Notice: equal loudness points not comparable with equal annoyance points have been omitted from the loudness curves.

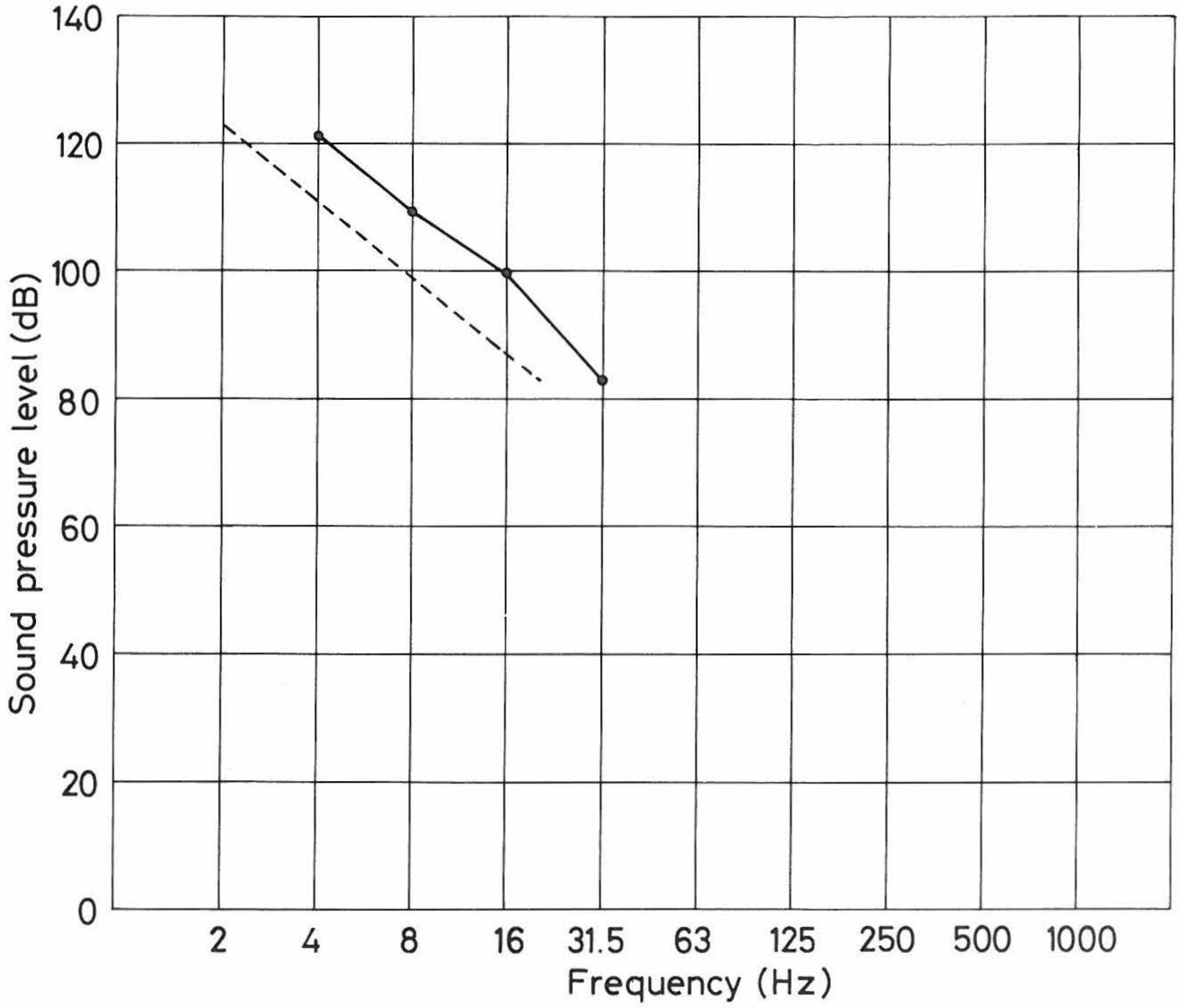

Figure 5. The filled circles represent means for Question 3 (unacceptable annoyance) converted to sound pressure levels. The dashed line has a slope of 12 dB per octave and passes 95 dB at 10 Hz; thus the line represents the upper limit of exposure that will result if our suggested criterion of 95 dB is used in connection with the ISO P-weighting curve.

The electronic equipment used to generate and control the sound. The computer is in an adjacent room.

Measurement of the sound field at the position of the subjects head.

The test chamber with the easy-chair (extreme left), infrasound loudspeakers behind the cloth (back-left), newspaper at the table and audiosound loudspeaker (right).

A subject under test.

A subject during adjustment of the lkHz reference noise.

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This monograph presents investigations and experiments carried out at Institute of Electronic Systems, in the period 1976-83. The manuscript has been accepted by the Faculty of Technology and Science at Aalborg University for the degree of Licentiatus, the Danish Ph. D. degree.

The book consists of 4 articles that have appeared or will appear in the Journal of Low Frequency Noise and Vibration. In addition to the four papers a brief summary is given in English and Danish.

The four papers have been chosen to give the best description of the research on infrasound carried out at Institute of Electronic Systems. During the project period a number of conference papers and reports have been prepared. A list of these is also included, together with a total list of literature on infrasound that has contributed to the selection of items for the work.

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