NOISE RADIATION FROM DRILL STEELS
and other experimental investigations
in acoustics and fluid mechanics

by

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av

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AKADEMISK AVHANDLING

som med vederbörligt tillstånd av Tekniska Fakultets-
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This doctoral thesis includes the following papers:


D Analysis of the fundamental frequency of the human voice and its frequency distribution before and after a voice training program, together with Sven Wedin. A shorter version of this paper has been published in Folia Phoniatrica 34:143-149 (1982).

The content of paper C is to be published in a condensed form.
Abstract

Drill rod noise has become a major noise source in percussive drilling. Generation of flexural waves, which seem to be responsible for most of the noise, is studied in a model with dynamic photoelasticity and in the real drill rod with strain gauge technique. The effect of the holder of the drill rod is investigated, and it is found, that the amplitudes of the flexural waves can be decreased by introducing visco-elastic damping material in the holder. It is also shown, that this will decrease the emitted noise.

Generation and propagation of turbulent spots on a water table are studied. A new photographic technique is developed to register structures within the spot. Streaks elongated in the streamwise direction are found to penetrate the spot, and it is observed that undulations on the streaks lead to chaotic motion. Comparisons with theory show that the theory accounts fairly well for the spreading angle, whereas the propagation speeds are larger than the observed values.

Tape-recordings of test subjects before and after a 5-day voice training program are analysed to find objective measures of changes in the voice. Frequency analysis shows, that the fundamental frequency and the variation are increased. It is also shown that the amplitude of the formants above 1000 Hz are increased compared to those below 1000 Hz.
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Introduction

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References

Paper A: A dynamic photoelastic study of flexural wave propagation in a model of percussive drilling.

Paper B: Reduction of noise radiation from drill steels, an experimental investigation.

Paper C: Observations of turbulent spots on a water table.

Paper D: Analysis of the fundamental frequency of the human voice and its frequency distribution before and after a training program.

Keywords: Photoelasticity, high-speed photography, flexural waves, drill rod, noise, mechanical impedance, turbulent spots, water table, voice-training, frequency analysis.
Introduction

Noise from percussive drilling machines has for many years been a major environmental problem in for example the mining industry. Noise levels from undamped machines in the range of 110-120 dB(A) are usual. At first the effort to reduce noise levels were concentrated on the machine itself. Different types of mufflers were designed, which decreased the noise radiation from the surface of the machine and the noise coming from the compressed air exhaust (1). A major step towards quieter drilling machines was taken when hydraulic drilling machines were introduced. This improvement focused the interest on the drill steel itself, as measurements showed that noise radiation from the drill steel now had become a major noise source.

To understand how to silence a drill without decreasing its drilling performance, it is necessary to understand how a rock drill works. A piston oscillates backwards and forwards under the action of compressed air. At the end of the down-stroke the piston impacts the shank of the drill rod, and the kinetic energy in the piston is transmitted as a longitudinal stress wave through the rod. Between two strokes the rod is rotated. At the moment of impact, the bit is held in contact with the rock. When the stress wave reaches the bit, the energy drives the cutting edge of the bit into the rock. The initial pulse will be reflected back and forth in the rod many times between successive blows.
Much experimental and theoretical work has been carried through, to optimize the longitudinal stress wave with regard to its ability to break the rock. It has been clear, that the longitudinal wave motion is not the only type of wave present in the rod. Flexural waves will be created through several mechanisms. Shimizu and Takata (2) has shown theoretically that two sources for flexural wave generation are eccentricity in the blow and propagation of a longitudinal pulse in a curved rod.

Both the longitudinal and the flexural wave are acoustic sources, the longitudinal wave being a monopole and the flexural wave a dipole. It is well known (3) that the monopole is a more efficient radiator than the dipole. The question is then if the longitudinal waves are responsible for most of the noise radiating from the drill rod. Physical intuition leads to the assumption that this is not the case. The energy necessary for bending the steel rod must be less than the energy for dilatation. This is confirmed in (4) where Hawkes et al show, that there is a correspondence between peaks in the noise spectrum from the rod and the natural frequencies of flexural vibrations of the rod and thus that the noise is most likely due to flexural motion.

The first attempt made to reduce the noise coming from the drill rod was to shroud the rod. Visnapuu and Jensen 1975 (5) centered a tube around the drill rod and filled the tube with a viscoelastic material. The result was at first promising. They reported a noise reduction of the order of
10 dB(A). However this technique has not proved practical. The reason is that the viscoelastic material inside the tube disintegrates due to heating. Another approach taken by Hagbjaer (unpublished) was to insert visco-elastic materials into channels in the rod. The damping effect after this treatment was good, but again the damping material disintegrated from the steel, this time due to the high vibration levels.

In paper A the problem of drill rod noise damping is approached in a new way. To get an overall information about the stress levels in the drill rod, a photoelastic model is used to study generation mechanisms of flexural waves and ways of introduce damping. The advantage with the photoelastic technique is that it gives information about stress levels in an area instead of just point-wise information. To record the propagation of the waves the photoelastic technique was combined with high-speed photography. An image converter camera with a framing rate of 200,000 frames per second is used, which gives an exposure time of 1 μs, enough to freeze the motion. The result shows that non-symmetric end-conditions, when the flexural wave reflects off the end of the rod, is a very important source for flexural waves. It is also shown that propagation of longitudinal waves in a curved rod will cause flexural waves. Both these conditions are very hard to influence. It is therefore necessary to look for means to damp the flexural vibrations in the drill steel. Attempts to do this with shrouding and insertion of visco-elastic material in the
rod have so far been less successful. The approach taken in this work is to change the boundary conditions in the holder in such a way, that flexural waves are absorbed instead of being reflected off the holder and thus allowing high amplitudes to be built up. This idea is theoretically treated in (6) by Lesser. Damping in the model was achieved by introducing a rubber-like material in the holder. The result shows a substantial decrease of the stress level both for the reflected wave and inside the holder.

Paper B is a continuation of the work in paper A, the interest now focused on the holder. Instead of working with a model, measurements are made on a real drill steel with strain gauge technique. Different visco-elastic materials are investigated. Along with this experimental study a numerical study was performed by Karlsson. To make comparisons between this study and the experimental results, the dynamic modulus of elasticity and the damping factor are determined for the materials used. The results are a confirmation of the results obtained in paper A. By introducing damping material in the holder, the level of the flexural waves are decreased both for short and long periods of time. This shows that the idea of changing the design of the holder is promising. Even greater improvement could be made, if the shank of the drill rod is made longer. Finally noise measurements were carried out in a realistic drilling situation. The measurements were made in the near field of the drill rod. The result shows a decrease in the emitted noise with about 3 dB(A).
Paper C is an experimental study of transition from laminar to turbulent flow on a watertable. Turbulent spots are generated, when a water drop is impacting the surface of the water flow. The development and propagation of the spots are studied for flows with Reynolds numbers between 1100–1800 and parameters such as lateral spread and propagation velocities are determined. To study the internal structure of the spot, a new photographic technique was developed. The technique used is single-shot photography with a direct registration on a photographic paper located below the glassplate of the watertable. The two main advantages with this technique are optimum resolution and one to one reproduction of the spot. With this technique it was possible to record streaks in the spot and undulations on these leading to chaotic motion. Gustavsson has theoretically studied direct resonances between the vertical velocity and the vertical vorticity (7). His result predicts the distance between wave crests for amplified waves. In the experiment some of the spots show a streak spacing which roughly corresponds to one of these resonances. The idea for the photographic procedure was due to Ögren.

Paper D is concerned with changes in the human voice after a voice training program. The existence of a difference in the voice quality is well known and is easily noticed by just listening to tape recordings of the test subjects before and after the voice training. It is however felt that a need exists for an objective measure of these changes. In the present work acoustic measurement technique is used
to determine the fundamental frequency, the variation of
the fundamental frequency and the spectrum of the voice.
The measurements and their statistical analysis were the
work of the present author, Wedin's part being concerned
with the voice training aspect of the investigation. Single
parameters are introduced to describe the changes. The
result shows, that it is possible to complete the subjective
estimations now made with objective measures of the effect
of a voice training program.

The common threads that run through this work are to be found
in the interactive use of photographic or visual methods
and transient measurement procedures. Papers A and B corre-
late the two in the search for the sources and suggestion
for a reduction of noise in drill steels. Similar methods
of signal analysis are also applied in paper D to study a
much more benign acoustic source, the human voice, while
paper C makes use of photographic methods to clarify some
difficult aspects of the problem of the transition from
laminar to turbulent flow.
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My gratitude is also expressed to Dr Håkan Gustavsson, who is coauthor of paper C, to Dr Lennart Karlsson for his efforts on the numerical calculation of drill steel motion and to Dr Nils-Erik Molin for his help with optical measurement procedures.

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References


A DYNAMIC PHOTOELASTIC STUDY OF
FLEXURAL WAVE GENERATION IN A MODEL
OF PERCUSSIVE DRILLING.

by

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Summary

The development of the percussive drilling machine has led to a situation where the drill steel itself has become a major noise source. A qualitative theory for the generation of this noise is presented. In this theory the longitudinal drilling pulse is partially converted to flexural motion by non-symmetric boundary conditions. The technique of stress optics combined with high speed photography is used in conjunction with araldite models of the drill steel to verify the above conjectures. The models are then used to demonstrate the importance of the clamping conditions in preventing the growth of noise producing motions of the drill steel. It is also shown that the araldite models give a reasonable representation of the stress wave pattern in a true drill steel, at least for the time period associated with the first few passes of the primary stress wave pattern and its reflexions.
1. Introduction

For many years the problem of dealing with the noise generated by percussive drills has focused on the machine's driving mechanism. With the introduction of hydraulic drills a substantial reduction in the overall noise level has been achieved, and interest has shifted from the motor to the drill steel itself as the major noise source. This is confirmed for example by measurements made in the reverberent room in our acoustic laboratory. The measurements were made with only the drill steel inside the measurement area, the machine itself being outside the room. The result showed that a 1.5 meter long drill steel gave a noise level as high as 105 dB(A). In order to reduce the noise produced by the steel, one must understand at least some aspects of the generation mechanism. A number of investigators have concerned themselves with various aspects of the problem. Carlvik (1) has carried out a mathematical study of the effect of non-symmetric boundary conditions in producing transverse waves from pure longitudinal excitation. Shimizu and Takata (2) have calculated the transverse waves produced by longitudinal waves on a curved rod. Lemcke (3) has examined the possibility of a "sonic-boom" produced by the Poisson ratio effect when a longitudinal stress pulse travels down a rod. The stressed area moves down the rod as a deformed region at a speed far greater than the sound speed in air. This causes Mach or shock waves to be formed in the surrounding atmosphere at the leading edge of the
pulse, which as Lemcke pointed out could induce a sharp transient disturbance in the region near the steel. Various experiments have been made in conjunction with these works. The measurements have fallen into two general classes, indirect and direct. Indirect measurements assess the state of the noise field and deduce the possible rod stress states from the acoustic radiation pattern. Direct measurements use strain gauges or other strain measuring tools to measure the rod deformation pattern directly.

When it comes to the practical matter of removing the noise several general approaches have been suggested. Following accepted principles of acoustic noise reduction investigators at the Bureau of Mines (4) have examined shrouded drill steels. A decrease in the emitted noise was found, however the method has not come into general use mainly due to heating problems in the enclosed space. Another approach taken by Haghjar (unpublished) has employed various versions of constrained layer treatments e.g. by inserting visco-elastic materials into channels in the rod. The problem with this method is that the vibration levels are so high that the visco-elastic material detaches from the steel. A recent and somewhat novel approach taken by the Fagersta Corporation uses the concept of an inner impact damping mechanism (termed a threshold limited vibration system).

The present work has two main purposes. The first was to make use of "model-studies" rather then the exact system
to examine the possible vibration states of the drill steel. This entails a certain amount of abstraction from the full system, but certainly a good deal less than normal to mathematical or numerical models. In the model studies attention is concentrated on the transient process of how the steady state vibration pattern is built up.

The second purpose is to set forth at least a qualitative model of the noise production process which can be used for future experimental design and for suggesting possible noise elimination procedures.

The use of models allow the introduction of stress optics and high speed photography into the study of the drill rod noise problem. This visual aspect of the work greatly assists efforts in explaining how the rods wave motions produce noise.

This problem has several possible applications. The one most in mind in the present study has been to gain an understanding of noise generation mechanism, however the mechanical integrity of structures undergoing dynamic loading and the production of stress concentrations due to wave-geometric interactions are other areas which can make use of similar techniques.

The paper is organised as follows. First a qualitative model of noise production in a percussive drilling machine is discussed. This is followed by a description of the
above mentioned model studies and is divided into two parts, one on the experimental techniques involved, the second in discussion of the various results obtained. The main conclusion of this work is that the means of drill rod support is of major importance in suppressing the noise, and the next section of this paper is devoted to this problem.


Figure 1 is a sketch of a percussive drilling machine. The work of the drill steel is performed by a stress pulse produced by a piston which strikes the drill steel with a frequency of about 50 Herz. Once the stress pulse reaches the working face the designer's main objective is over. His interest is in producing as pure a longitudinal pulse wave as possibly by the hammer blow. Thus in each cycle (one hammer blow) only a small portion of time is of interest to the designer whose main aim is breaking rock. The question of how noise is produced in this process has up to recent times been of little interest. In what follows we give a synthesis of the thoughts of several investigators.

The rod is long and thin and it is expected that the major part of the deformation pattern can be described in terms of the simple model of longitudinal and flexural vibration, that is the simple non-dispersive wave equation and the Bernoulli beam equation. It is well known that the former
Figure 1: Explanatory sketch of a percussive drilling machine.

1 Drillrod
2 Piston
3 Tilt valve
4 Air inlet
5 Air outlet
equation provides an adequate basis for the design of drill steels (5,6). For the purpose of the present work we can suppose a somewhat ad-hoc or phenomenological model where these disturbance modes are coupled. In addition we can treat the complicated support and working face conditions with simple impedance models. In the present work we will only make conceptual use of the model to see what might be expected in a typical event.

From the viewpoint of the acoustic noise field the longitudinal disturbance provides a swelling of the steel and hence an acoustic source moving along the rod. On the other hand the flexural disturbance can be considered as the sum of two polarized orthogonal transverse moving disturbance patterns which have the form of acoustic dipoles. Intuitively one expects it to be less energy consuming to bend a rod rather than to induce a bulk change, and for this reason one might expect more acoustic energy to result from flexure as opposed to longitudinal motion. An acoustic source is more efficient as a radiator, however because of the above reasoning it is generally felt that flexural waves are the main noise source on drill steels. Measurements have been somewhat contradictory and it still can not be stated with certainty that this is indeed the case. Also the designer of percussive drilling machines tries to clamp the steel in such a manner as to prevent the loss of energy from the hammer blow into flexural motion as it is the longitudinal stress pulse.
which is mainly responsible for the task of breaking rock. One must then ask the question, where do the flexural waves come from. The conceptual model of coupling between the longitudinal and flexural modes of rod motion provides three possible sources of flexural disturbance. To explain this let us follow a typical event. Though it is quite difficult to produce an impact in which only longitudinal waves are generated assume that this is the case. The hammer strike generates a pure longitudinal or bulk wave which travels down the rod. The stress pulse arrives at the working face and carries out it's main task of breaking rock. There now remains time for about fifty passes of the pulse back and forth between the machines clamping mechanism and the broken working face before the next hammer blow. Thus when the longitudinal pulse reflects off the nonsymmetrical rock surface transverse forces will produce a flexural disturbance on the rod. When the flexural pulse arrives at the "rigid" clamp it will meet boundary conditions that are ideal for the reflection of the transverse disturbance. As will be noted below, the returning longitudinal pulse reflecting from the support also appears to induce flexural motion, though this may be attributed to the fact that a truly rigid and symmetric support is impossible to attain in practice. As the process continues the rod will bend. The low frequency buckling of the rod will not generate noise, however it will provide a curved channel for the longitudinal pulse. This means that a further source of high frequency flexural motion will be provided by the
continual interaction of the longitudinal pulse with the curved rod surface.

3. Description of the model studies

A. Experimental techniques

The highspeed photoelastic method makes it possible to get more than only pointwise information about the wave propagation. This is an important advantage compared to for example strain gauge techniques. One has of course to be aware of the differences that exist between the real steel and the model material used. A suitable model material for dynamic investigations is Araldite B, CT 200. An earlier study (7) has shown that this material upon loading undergoes an increase in its modulus of elasticity, however there is no change in the fringe constant due to a decrease in the longitudinal strain per fringe. The wave speeds for both longitudinal waves and flexural waves are much less in the model than in steel. The longitudinal wavespeed in Araldite is 1600 m/s compared to 5000 m/s in steel. Another difference is that the damping in the model material is greater than in steel. Damping can be measured as the distance the wave has to travel before its amplitude has decreased to one half of its initial value. This distance is for our model material of the order of two to three metres while for steel it is several hundred metres. This
means that there are scale problems when investigating how the wave pattern develops after several reflections. The present study is concerned with the manner in which steady state vibrational states build up hence the first few passes of the wave along the rod are of main concern. Therefore the problem of wave attenuation due to the Araldites damping properties is not of major concern.

Another limitation with the photoelastic method is that one has to work with two dimensional models to avoid the use of rather sophisticated methods to unravel the optical information. In our case the drill steel is axisymmetric which makes a two-dimensional study possible. The model rod has in all experiments a cross-section of 10x15 mm$^2$ and a length of 300 mm. A support was designed to give approximately the same boundary conditions as for the real drilling machine. By that we mean that the drill steel is free to move in a direction parallel to its axis but not perpendicular to it.

An ordinary circular polariscope consisting of two polarizers and two quarter wavelength plates was set up. See figure 2. By this technique it is possible to eliminate the isochlines leaving the isochromes unaffected. They correspond to the difference in stress between the principal stress components. By turning the quarter-wavelength plates it is possible to get both light and dark-field illumination. Ordinary xenon flashlamps were used as light sources. By firing them in
Figure 2: The experimental set-up.
1 Lightsource
2 Filter
3 Positive lens
4 Polariscope with model
5 Imacon high-speed camera
6 Delay unit
sequence we were able to get long enough illumination time. The spectral distribution of a xenon lamp is broad with its maximum amplitude in the blue region. This gives rise to an unwanted broadening of the fringes in the stress-optic pattern. To decrease this broadening we filtered the light with a high quality filter, which had its maximum transmission at around 400 nanometres, the same wavelength as the maximum amplitude for the lightsource.

The highspeed camera was of the image converter type (Imacon 790) capable of framing speeds up to 20 million frames per second. The framing speed suitable for our experiment turned out to be 200,000 frames per second. One further problem is to trigger the camera and the light-sources in a reliable and repeatable way. This was achieved by mounting a strain-gauge onto the rod close to the point of excitation and feeding the amplified signal from that into a delay unit.

4. Experiments

A. Conversion of longitudinal waves into transversal waves

As mentioned in the introduction there are three main possible ways in which some of the energy in the longitudinal wave can be converted into flexural waves. To get experimental evidence for these possibilities the following experiment was set up. A pure longitudinal wave was excited by hitting
the end of the rod with a pendulum. The wave, after travelling down the rod, was reflected off a block of steel. To get a nonsymmetric boundary condition during reflection, a small wedge was glued onto the end of the rod. The result is showed in plate 1. In the first three frames the longitudinal wave traveling from left to right reaches the end of the rod. From frame number four and on the longitudinal wave is reflected. In frame eight it can clearly be seen that a flexural wave is generated (marked by A in the plate) and in the following frames the wave travels to the left with increasing amplitude. It is also possible to determine an approximate value of the velocity of the longitudinal and the flexural wave. A direct measurement on frames 7-11 of the position of the respective wavefronts gives, after taking the scale factor into account, a velocity of the longitudinal wave of 1500 m/s and the flexural wave of 900 m/s. This is in reasonable agreement with the wave-speeds that can be calculated from the density and the modulus of elasticity for the model material used. The sequence shows that this type of boundary condition will initiate a transversal wave. A nonsymmetric impact will give a similar result. That situation will arise if there is a lack of rod alignment in the chuck, or if the end of the piston or the drill rod is damaged due to wear.

To investigate the influence of an initial curvature on the rod the second experiment was designed, where a longitudinal wave excited in the same way as above was sent through a bent
Plate 1:  

a) Sketch of end condition.

b) Generation of a transversal wave from non-symmetric reflection. Interval between frames is 5 μs. The time indicated in the lower left corner on this and the following plates is the time between the wave reaching the straingauge and the exposure of the first frame.

A: Wavefront of the flexural wave.

B: Wavefront of the longitudinal wave.
section of the rod. The result can be seen in plate 2. The free end of the rod is inside the field of view. In the first three frames one can follow the front of the longitudinal wave travelling from right to left. In frame four which is exposed 20 μs after the passage of the longitudinal wavefront a flexural wave is generated. The amplitude of the flexural wave is increasing in the next few frames. The last four frames show the flexural wave traveling towards the right after reflection.

B. The influence of the clamping mechanism on flexural waves

The previous experiments clearly show that the flexural waves are created when the longitudinal wave travels down the bent drill rod and when it reflects off the nonsymmetric boundary condition at the working face or when it is excited non-axially. Aside from the possibility of some "active" control mechanism, the working face boundary condition is outside the hands of the designer. The way the drill rod is currently fixed to the machine, the clamp is an almost perfect reflector of flexural waves. As the time between two strikes of the piston permits the flexural wave to make many back and forth passes along the steel, a substantial decrease in the emitted noise should result from changing the boundary conditions in the holding mechanism from a perfect reflector to an absorber of most of the energy. To examine the possibilities of doing so the following experiment was set up.
Plate 2: Flexural wave generated in a bent section of the rod.

a) Sketch of the endcondition.

b) The flexural wave is marked by A in frame four and is traveling to the left.
As the interest is now focused on flexural waves only, the excitation method was changed. To produce only flexural waves the model of the drill rod was impacted from the side with a plastic cylinder. As the flexural waves are dispersive, a considerable blur of the fringes occur due to the difference in phase velocity for different frequencies. To produce a tight wavegroup a support was introduced on the opposite side of the rod two centimeters above the point of excitation. That support allowed only a fixed part of the rod to vibrate during the initial part of the excitation and thus acted as a frequency filter. Plate 3 shows the generation of transversal waves with this technique. In the first frame the plastic cylinder just hits the rod. In the following two frames a cylindrical wave is diverging from the point of excitation. In frame four the wave reaches the opposite side which is free. There the compression wave reflects off as a tension wave travelling back towards the point of excitation. In the next few frames these waves will interact and superimpose to give the recorded stress pattern. Plate 3 c) shows the transversal wave group in a later stage. Note the symmetry in the stress-optics pattern. At a given distance away from the point of excitation one side of the rod is under tension while the other side is under compression. This cannot be seen directly from the stress pattern. To make sure that the excited wave was flexural use was made of the so called finger nail test. By applying a point load on each side of the rod and then examining the distortion of the stress-optics pattern close
Plate 3: a) Sketch of the set-up for generation of flexural waves.

b) The development of flexural waves immediately after impact. Observe the angle between the impacting cylinder (A) and the rod, which gives a point excitation.

c) A flexural wavegroup traveling down the rod. The support marked by an arrow can be seen on the left hand side of the rod.
to these points it is possible to decide whether this part of the rod undergoes tension or compression.

Flexural wave groups produced by the above method were then used to investigate two different types of clamping mechanisms. The first modelled the currently used clamping method. In the model this corresponds to the holder being made of the same material as the rod. The result is shown in plate 4, where the first frame is exposed 300 μs after the impact. In the first frame the flexural wave coming from the top has arrived at the clamp. If one compares frame one and two there is almost no difference in the stress pattern. That corresponds to the wave just being reflected off the support. A comparison between frames three, four and five shows that the flexural wave now is on its way back up the rod. This is clearly visible if one follows the light fringe marked by an arrow in the frame four. It is also interesting to note the high stresses developed inside the clamping mechanism. The boundary condition in the clamp was then changed by introducing a rubber surface. A soft material like rubber will change the boundary condition from one that reflects all of the incident energy to one of absorption, or transfer of the energy to the clamp where it will be dissipated. Plate 5 shows the result. The illumination is now darkfield in contrast to plate 4. It is therefore not possible to localise the clamp. Its position is however exactly the same as in plate 4. The stress-optics pattern shows a significant difference. The
Plate 4: a) Sketch of the model of the holding mechanism. 
b) Transversal wave reflected off the holding mechanism. Note the high levels of stress inside the holder.
Plate 5:  
a) The stress pattern from the flexural wave with a soft holder. The picture is taken with dark-field illumination. The arrows point at the upper end of the holder.
b) The same field of view as in a) but 240 µs later. The stresses are low and most of the energy is absorbed by the rubber.
flexural wave is now continuing inside the clamp instead of being reflected off it. The stress magnitudes are also much less as can be seen from the number of fringes. The first frame of the last figure is exposed 540 µs after the time of excitation. These frames show a further decrease in stress magnitude due to absorption in the clamp.

5. Conclusions

The first series of experiments clearly verifies the three above postulated flexural wave generation mechanisms. The result of the last experiment shows that the influence of the boundary conditions in the holding mechanism is of great importance to the reflection of flexural waves. By introducing a material in the holding mechanism capable of absorbing the energy in the flexural wave it is possible to get a substantial reduction in the amplitude of the reflected wave and thereby a possible decrease in the emitted noise from the drill rod. Further analytical and experimental investigations are being carried out to find which material parameters are important and their optimal values.

Aside from these immediate practical aims the work shows the utility of combining high speed photography and stress optics to study the mechanisms which produce noise in a device. The advantage of the visual results so obtained far outweigh the difficulties of interpreting the implications
of the model studies with the actual device. While many of the noise production mechanisms are classical the model studies allow quite complicated interaction effects to be studied, and permits the acoustic scientist to provide striking visual proof to the designer. Considering the history of the present problem, it is clear that such proof is needed in order to implement any radical changes in design philosophy.

Several interesting theoretical problems arise from the above studies. The manner in which the flexural wave interacts with the clamping mechanism must involve a number of possible optimum design strategies. It is hoped that further studies of this aspect of the problem will enhance that effort. As noted in the introduction it has been known for some time that curvature on the steel can produce flexural waves from longitudinal ones. The full understanding of this mechanism is of interest as it involves low frequency inaudible flexural or buckling motions that modulate high frequency longitudinal motions in an extremely complex interactive pattern. The full elucidation of this is far from complete.

It must be acknowledged that the present studies are mainly qualitative in nature, providing vivid demonstrations of various conjectures but little in the way of detailed quantitative information. For this reason experiments have been designed to use more classical pointwise strain
measuring techniques to complete the picture given in the present study. The results of these efforts will be presented in a sequel to the present paper.
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REDUCTION OF NOISE RADIATION FROM DRILL STEELS,
AN EXPERIMENTAL INVESTIGATION

by

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Summary

A mechanical impedance technique is used for measuring material parameters for some visco-elastic compounds. The results are used in a numerical study, which will be reported separately.

The same visco-elastic materials are used in a drill steel holder, to investigate their influence on flexural waves. Strain gauges are used to measure the amplitude of the wave motion in the steel. It is found that visco-elastic material in the holder will change the boundary condition in such a way, that the amplitude of the flexural waves will decrease.

Noise measurements are carried through in a real drilling situation. The results show a decrease in the emitted noise from the drill steel.
LIST OF SYMBOLS

A - area of test rod

C - phase velocity of flexural wave

E - dynamic modulus of elasticity

E* - complex modulus of elasticity

F - force

f - frequency

l - length of test rod

M_a - mass of support for test rod

M_R - mass of test rod

Z - mechanical impedance

\( \beta^* \) - complex parameter \( \beta^* = \omega / \sqrt{E^*} \)

\( \gamma \) - wavenumber of flexural waves

\( \delta \) - logarithmic decrement

\( \varepsilon \) - strain

\( \eta \) - damping factor

\( \xi \) - displacement

\( \rho \) - density of test rod

\( \sigma \) - stress

\( \omega \) - angular frequency
1. Introduction

In [1] the generation and propagation of flexural waves in a model of a drill rod and its holder were studied with a dynamic photoelastic method. The result showed, that possible generation mechanisms for flexural waves are non-symmetric conditions, when the piston hits the rod, non-symmetric end conditions at the rockface and propagation of longitudinal waves in a curved rod. It was also shown, that the boundary conditions in the holder of the drill rod had a great influence on the reflection of an incoming flexural wave. If the same material was used in the holder as in the drill rod, the flexural wave was reflected off the holder with approximately the same amplitude as the incoming wave. If however the holder was made of a soft material, part of the incoming wave was absorbed in the holder. These results were qualitative, and it was therefore felt, that quantitative measurements should be made on a real drill rod to verify the results obtained in the model experiments.

The first part of this paper contains results from measurements of the dynamic modulus of elasticity and the damping factor for some visco-elastic materials. The reason for these measurements was to use the material parameters so obtained in a numeric study of flexural wave propagation and damping in a rod. Comparisons between the numerical results and results from the strain gauge measurements reported in this paper can then be made. These results will be presented in a separate paper.
The second part presents, after a general discussion of the special problems associated with an experimental study of flexural wave propagation, results from strain gauge measurements of flexural waves.

The last part of the paper shows results from measurements of the noise level when actually drilling with different materials in the holder.
2. Measurements of dynamic Young's modulus and damping factor.

When a linear visco-elastic material is subject to time-dependent variations of stress and strain, the stress is no longer related to strain by a simple constant of proportionality, Young's modulus of elasticity, "E". A viscous friction force has to be taken to act in addition to the elastic forces. Such a friction force is proportional to the time-derivative of the strain and the relation between stress and strain takes the form

\[ \sigma = E\varepsilon + E'\frac{d\varepsilon}{dt} \]  

(1)

For sinusoidal time-variations

\[ \varepsilon = \varepsilon_0 e^{i\omega t} \]  

(2)

one finds that

\[ \sigma = (E+i\omega E')\varepsilon \]  

(3)

Young's modulus now takes the form

\[ E^* = E(1+i\eta) \]  

(4)

and is the complex modulus of elasticity where E, the real part, is the dynamic modulus of elasticity and \( \eta = \frac{\omega E'}{E} \), the imaginary part, is the damping factor.
Equation (3) shows that if the strain variation is periodic, stress and strain are not in phase with each other. This phase difference implies that mechanical energy is lost in the material.

The complex modulus of elasticity is an important material parameter. To be able to make comparisons between experimental measurements and numerical calculations of the flexural wave-motion on the drill rod, it is necessary to determine the dynamic modulus and the damping factor for the materials used in the experiments.

There are basically two different types of methods available when measuring the complex modulus of elasticity, resonant and non-resonant methods [2]. Two examples of resonant methods are the frequency response method and the reverberation method. In the frequency response method the sample is forced into flexural vibrations from an external source. The amplitude of the vibration is measured by a displacement sensitive pick-up. The amplitude is plotted versus the frequency. An example of such a curve is shown in figure 1.

![Frequency response curve](image)

Figure 1: Frequency response curve of a sample. $f_n$ is the resonance frequency of the $n$'th harmonic and $\Delta f_n$ the bandwidth.
The damping factor can be calculated as

$$\eta = \frac{\Delta f_n}{f_n}$$

(5)

$\Delta f_n$ being the bandwidth of the resonance peak and $f_n$ the resonance frequency. The real part of the complex modulus of elasticity can be found from the resonance frequency, as the mechanical dimensions and the boundary conditions of the sample are known. In the reverberation method the sample is again excited at its resonance frequency. The external force is then suddenly turned off, and the amplitude versus time is recorded on a logarithmic level recorder. The decay will appear as a straight line, and the damping factor can be determined from the reverberation time, defined as the time it takes for the amplitude to drop 60 dB.

In this work we have made use of a non-resonant technique, the progressive wave method. This method is based on the theory for longitudinal vibrations in internally damped rods [3]. Let $E^*$ be the uniform complex modulus for a given temperature. Consider a rod with uniform cross-section, which is long compared with the wavelength. A sinusoidal force is applied to one end of the rod. The forces on an elementary segment of the rod are

$$F(x) = -AE^* \frac{\partial \xi}{\partial x}$$

(6)

$$F(x+dx) = -AE^* [\frac{\partial \xi}{\partial x} + \frac{\partial}{\partial x} (\frac{\partial \xi}{\partial x}) dx]$$

(7)
where $x$ and $x+dx$ are the coordinates for the segment and $\xi$ is the displacement. Newton's second law now gives

$$\frac{\partial^2 \xi}{\partial x^2} = \frac{\rho}{E*} \frac{\partial^2 \xi}{\partial t^2}$$

(8)

where $\rho$ is the density of the rod.

This is the well-known wave-equation for longitudinal waves in an undamped rod with Young's modulus replaced by its complex counterpart. If $\xi$ is varying sinusoidally with time

$$\xi = \xi_0 e^{i\omega t}$$

(9)

and equation (8) now becomes

$$\frac{\partial^2 \xi}{\partial x^2} + \beta^* \frac{\partial^2 \xi}{\partial t^2} = 0$$

(10)

where $\beta^*$ is a complex parameter

$$\beta^* = \omega \sqrt{\frac{\rho}{E*}}$$

(11)

A solution to the wave-equation has the general form

$$\xi^*(x) = A e^{i\beta^* x} + B e^{-i\beta^* x} = C \sin \beta^* x + D \cos \beta^* x$$

(12)

Consider a rod with mass $M_R$ which is rigidly terminated at $x = 1$. 
Figure 2: Rigidly terminated rod.

A sinusoidally varying force $F_0$ at $x = 0$ will give a sinusoidally varying displacement.

The boundary conditions are

$$\xi(1) = 0 \quad (13)$$

$$\frac{F_0}{A} = -E\frac{\partial \xi(0)}{\partial x} \quad (14)$$

Differentiating (12) with respect to $x$ gives

$$\frac{\partial \xi^*}{\partial x} = \beta^*(C\cos\beta x - D\sin\beta x) \quad (15)$$

and with the boundary conditions inserted in equations (12) and (15) gives

$$C\sin\beta I + D\cos\beta l = 0 \quad (16)$$

$$\frac{F_0}{A} = -E'C\beta^* \quad (17)$$
The point impedance at \( x = 0 \) is

\[
Z = \frac{F_0}{i\omega \xi(0)} \quad (18)
\]

where \( \xi(0) = D^* \) from (12).

(16) and (17) can now be solved for \( D^* \).

If the point impedance \( Z \) is normalized with the mass \( M_R \) of the rod

\[
\frac{Z_m}{i\omega M_R} = -\frac{\cot \beta^* \Im}{\beta^* \Re} \quad (19)
\]

This result can be used to measure the dynamic Young's modulus and the damping factor for different materials by measuring the point impedance and then solving the equation for \( \beta^* \) [4]. The complex modulus of elasticity can then be obtained from equation (11)

\[
E^* = \frac{\omega^2 \rho}{\beta^*} \quad (20)
\]

The experimental set-up consists of an electro-magnetic exciter, an impedance head, charge preamplifiers and instruments for measuring the magnitude of the force and the acceleration and the phase difference between them. As the measured materials are soft, the driving platform of the impedance head must have a greater contact area, than what
is needed for measurements on a metal structure. The impedance head used in our experiment was Brüel and Kjaer type 8000 with a contact area of 1.75 cm².

Figure 3 shows a block diagram of the experimental set-up.

The impedance head measures acceleration and force and equation (18) has consequently to be rewritten. As the applied force is sinusoidal the acceleration
\[ \ddot{\xi} = \omega^2 \xi/\omega t^2 \]
and
\[ F/\dot{\xi}^2 = -\frac{\cot\beta*1}{M_R*1} \]

(21)

To attain the condition that the rod is rigidly terminated the mass \[ M_a \] in figure 3 is much greater than the mass \[ M_R \] of the rod.

When measuring impedance with an impedance head one has to be aware of an error introduced by the mass of the driving platform. This platform is located between the piezo-electric disc and the measuring object and is therefore representing an impedance \[ Z_m \].

A recording of the impedance of the unloaded impedance head will approximately be a straight line with a slope of 6 dB per octave. This means that the impedance of the driving platform will have an increasing influence on the measured impedance of an object with increasing frequency. When the
Figure 3: The experimental set-up.
Exciter Derritron VP 30; Preamplifier Brüel & Kjaer 2635,
Measuring amplifier Brüel & Kjaer 2606, 2608; Vector voltmeter
Tekelek Airtronic Autophase TE 1700; Oscilloscope Tektronix 468;
Reference Generator Newtronics 200 MSTFC
impedance head is attached to a structure the point impedance $Z_m$ of the impedance head and the impedance $Z_0$ of the structure form a series circuit because of identical velocity. Thus the measured impedance $Z_t$ is

$$Z_t = Z_m + Z_0$$

(22)

One way to correct for this error is to determine the impedance of the impedance head for different frequencies and subtract from the measured value. Another way, used in our experiment, is to compensate electrically for the impedance of the driving platform. The piezo-electric discs are mounted in such a way, that a phase shift of $180^\circ$ is created between the force and acceleration signals. If now a proper voltage is taken from the acceleration signal by voltage division, and this signal is added to the force signal, the result will be a zero output and the force signal is cancelled. The circuit used for this compensation is shown in figure 4 [5]. As the impedance $Z_t$ is frequency-dependent, this compensation cannot be optimal throughout the whole frequency range.
Figure 4: Circuit for electrical masscompensation. $F_1$ and $A_1$ are incoming force respectively acceleration signal and $F_0$ and $A_0$ is the outgoing signals.

The measurements were made for four different materials, three natural rubbers with different hardness, 67°, 70°, 80° Shore A, and Adiprene. The test samples were cylindric with a diameter of 16 mm and a length of 25 mm. The force, the acceleration and the phase-shift between those two were measured for a number of discrete frequencies in the range 50 to 5000 Hz under mechanically steady-state conditions. The measured values of acceleration and force obtained from the impedance head were first used to determine the impedance. Figures 5 and 6 are plots of impedance and phase angle versus the frequency for rubber 80° Shore and Adiprene. For low frequencies the rod acts like a spring. At higher frequencies the impedance has minimas where the
impedance changes from being springlike to being masslike. These resonances will of course affect the determination of the complex modulus of elasticity.

The measured values of acceleration and force are then used to determine the complex constant \( \beta^* \) with the Newton-Raphson iterative method, and the dynamic modulus of elasticity and the damping factor are then calculated from equation (11). The result is plotted as (•) in figures 7 and 8 as \( E \) and \( n \) versus frequency for rubber 80° Shore and Adiprene.

Examining the graphs one notices a dramatic decrease in the modulus of elasticity and an increase in the damping factor for certain frequencies. This does not mean that the material parameters suddenly change for those frequencies. It just reflects the fact, that there are resonance effects for frequencies determined by the geometrical dimensions and the complex modulus of the test samples. When this happens, this method fails in determining the complex modulus of elasticity for frequencies close to the resonance frequencies. To determine the modulus of elasticity for those frequencies as well, the measurements were repeated with a test sample of half the original length. This changes the resonance frequency to a region above 5000 Hz. The results for the same materials are plotted as (x) in figures 7 and 8.
Figure 5: Impedance and phase for rubber 80° Shore A.
Figure 6: Impedance and phase for Adiprene
Figure 7: Dynamic modulus of elasticity E and damping factor η for rubber 80° Shore A
• - sample length 25 mm
x - sample length 12 mm
Figure 8: Dynamic modulus of elasticity $E$ and damping factor $\eta$ for Adiprene
- $\bullet$ - sample length 25 mm
- $\times$ - sample length 12 mm
3. Strain gauge measurements.

In the following results from measurements with strain gauge technique of flexural wave propagation and reflection on a drill rod will be presented. A pair of strain gauges were mounted on opposite side of a drill rod and were connected to adjacent branches of a Wheatstone bridge to sense only the flexural and not the longitudinal part of the wave. The drill rod was a standard drill rod manufactured by the Fagersta Company with a total length of 980 mm. A holder was designed where the inner part could be changed to be able to make measurements on different materials. Plate 1 shows the holder and the exchangeable inner parts.

The first idea was to excite the flexural wave in the same way as in the real situation. This means that a piston is shot onto the end of the drill rod, and flexural waves are generated when the initial longitudinal wave is non-symmetrically reflected. Tests performed along these ideas showed however, that the repeatability was not good enough. We therefore changed our way of excitation. Instead of starting with a longitudinal wave we generated a flexural wave by hitting the drill rod from the side. This was done with a pendulum, which gave a very good repeatability. The length of the initial pulse is determined by the length of the pendulum, which was 80 mm, thus giving a pulse length of about 30 μs. The signal from the bridge was amplified and recorded on a Nicolet Explorer III A digital
Plate 1: The holder with exchangeable inner parts.
oscilloscope. The strain data were then transferred to a
desk-top computer, Hewlett-Packard 9845B, plotted and
stored on a tape. Figure 9 is a block diagram of the
different instruments used.

![Block diagram of the experimental set-up.]

**Figure 9**: The experimental set-up.

Numerous experiments have been carried through measuring
propagation of longitudinal waves on rods. If a well aligned
and good axial impact is obtained, it is possible to get a
well defined rectangular pulse. This longitudinal pulse can
then be studied at different positions along the rod and
effects of for example different boundary conditions can be examined.

The situation when working with flexural waves is however quite different.

Figure 10: Beam subjected to bending.

Consider the beam equation for the beam shown in figure 10 [6].

\[
\frac{3}{4}\frac{\partial^4 y}{\partial x^4} + \frac{1}{2} \frac{\partial^2 y}{\partial t^2} = 0, \quad a^2 = \frac{EI}{\rho A}
\]

(23)

If harmonic wave propagation is assumed

\[
y = Ae^{i(\gamma x - \omega t)}
\]

(24)

where \(A\) is the amplitude of the wave, \(\gamma\) is the wavenumber and \(\omega\) is the frequency. Equation (24) substituted in (23) gives a relation between frequency and wavenumber as

\[
\gamma^4 - \frac{\omega^2}{a^2} = 0
\]

(25)
By substituting $\omega = \gamma c$ in (25) a relation between phase velocity and wavenumber is obtained.

$$c = \pm ay$$  \hfill (26)

This relation shows that propagation of flexural waves on a beam is dispersive. High frequency waves will propagate faster than low frequency waves. This result however contains an anomaly due to an approximative formulation of the problem. When the wavelength goes to zero, the phase velocity goes to infinity. If rotary motion of sections of the bar is taken into account, and the assumption that rectangular elements of the bar remain rectangular is changed, one gets the Timoshenko beam equation and this anomaly will be eliminated, with an upper bound existing for the phase velocity.

The dispersive behaviour of flexural waves is clearly demonstrated in figure 11. The drill rod is hit at its free end and the strains are recorded at two positions along the rod, A 40 mm respectively B 395 mm from the point of impact. The first part of the recording from gauge pair A (channel A) shows the initial pulse and at later times effects from reflection off the holder. The recording from gauge pair B (channel B) shows the incoming initial pulse strongly distorted due to dispersion. Waves containing higher modes will arrive first to the gauge and give rise to the oscillatory behaviour of the strain signal.
It is also possible to determine the wave speed from these recordings, as the distance between the two pairs of strain gauges are known and the travel time for the flexural wave can be determined from the recordings. The maximum wave speed so obtained was 3015 m/s.
Figure 11: Distortion of flexural wave due to dispersion.
The aim with the strain gauge measurements was to compare the amplitude of the flexural wave entering the holder with the amplitude of the flexural wave reflected off the holder. The dispersive behaviour of the flexural wave makes this comparison difficult. If the wave has travelled such a distance, that different modes have been separated, information about the total amplitude is hard to retrieve. An obvious way to minimize this problem is to excite the wave close to the gauge and the holder, thus obtaining a short travel time for the incoming and the reflected wave. This was done by hitting the drill rod 5 mm to the right of gauge pair B. See figure 10. The result of these recordings are shown in figure 12. The total recording time was 1024 µs. As the reflected wave from the free end of the rod arrives at the gauge after about 400 µs, only the first part of the total recording is plotted.

The following events can be distinguished in the recordings. The different parts are marked in figure 12 b).

Part I: The initial flexural pulse. The risetime is about 40 µs.

Part II: Reflection from the front part of the holder.

Part III: Reflection from the rear part of the holder and the end of the drill steel. The difference in time between reflections from these parts is very small, only a few microseconds.
Part IV: The last part of the recording containing reflections from the free end of the drill steel.

As can be seen from the recordings, only part I contains a well-defined flexural pulse. When the wave returns to the gauges after reflection in the holder, high-frequency components arrive earlier than low-frequency components. This effect appears as oscillations on the strain signal. As the length of the holder is short compared to the distance between the holder and the gauges, the reflected waves from the front and rear part of the holder will overlap. A comparison of the amplitudes for the reflected wave for different materials in the holder is thus difficult to make.

The following conclusions can however be made. The difference between the four visco-elastic materials is small. This is as expected as they have in principal the same dynamic modulus of elasticity and the same damping factor.

To make a comparison for the steel holder easier, figure 12 e) is a plot of both steel and 70° Shore A in the same diagram. The strain level is lower for the rubber holder except for the time 200-250 μs. For this time the wave reflected off the steel holder shows several maxima, while the wave reflected off the rubber holder has one more pronounced maximum.
Figure 12: a) 67° Shore A  b) 70° Shore A
Figure 12: c) 80° Shore A  d) Adiprene
Figure 12: e) steel

70° Shore A
To investigate the damping properties of the different materials for longer periods of time, the drill steel was excited at its free end, and the strain signal from gauge-pair B was recorded during 2.04 s. This way of excitation entails, that all flexural modes of the drill steel are excited. However as the point of excitation is the antinode of the first resonance mode, this will be dominant. The results as strain level versus time are shown in figure 13.

It is immediately evident from the recordings, that the damping is much less for the steel than for the four visco-elastic materials. To get a measure of this difference the logarithmic decrement $\delta$ was determined, defined as

$$\delta = \frac{1}{n} \ln \frac{x_0}{x_n}$$

where $x_0$ is the amplitude of the first period, and $x_n$ represents the amplitude after $n$ cycles have elapsed. These values are found in table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$80^\circ$</td>
<td>0.16</td>
</tr>
<tr>
<td>$70^\circ$</td>
<td>0.45</td>
</tr>
<tr>
<td>$67^\circ$</td>
<td>0.40</td>
</tr>
<tr>
<td>Adiprene</td>
<td>0.25</td>
</tr>
<tr>
<td>Steel</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Table 1: The logarithmic decrement for the five different materials.
Figure 13: Strain versus time
a) Steel    b) Rubber 80° Shore A

The result from the strain gauge measurements shows, that a holder manufactured from a material with visco-elastic damping will decrease the amplitude of reflected flexural waves. However the most important question from the viewpoint of the user of percussive drilling machines is still left to be answered. Will there, if the clamping mechanism is changed, be a noise reduction from the drill steel in the real drilling situation? The only way to answer this question is to measure the noise coming from the drill steel when actually drilling. These measurements were carried through in the anechoic chamber at the acoustic laboratory.

The tests were made with a percussive drilling machine, an Atlas Copco RH658LS, working with compressed air as the driving power. To be able to make tests on different materials in the holder, the chuck of the drilling machine was slightly modified. The standard holder was replaced by a holder, where the same parts as used in the strain gauge measurements could be inserted. (See plate 1). Three different materials were tested, steel, natural rubber with hardness 67° Shore A and Adiprene. Parameters as air pressure and drilling force were kept constant for all test runs.

Many noise sources are contributing to the overall noise level when drilling with a percussive drilling machine. Examples of such noise sources are the machine itself, the
exhaust air from the machine and the noise coming from the rock face. As our aim was to measure only the noise coming from the drill rod several precautions had to be taken. Figure 14 shows the experimental configuration.

To eliminate influence of the noise coming from the machine, the machine was situated outside the measuring room. The drill steel was lead through the wall in a small tube. The rest of the wall opening was carefully insulated with heavy material, which gave a high noise reduction. To determine the contribution inside the room from the machine outside, the drill steel was disconnected from the machine, and the noise levels were measured. The noise level outside the anechoic chamber close to the machine was 98 dB(A) during drilling and 70 dB(A) inside. As the noise levels from the steel were in the order of 90 dB(A), this reduction was more than sufficient. Another noise source situated inside the measurement area was the piece of rock. To eliminate
the noise coming from the rock face during drilling, the piece of rock was carefully covered with insulation material. One more measure was taken to decrease the influence of not wanted noise. The distance between the microphone and the drill steel was kept small. The measurements were performed with the microphone situated 5 cm away from the drill steel.

The signal from the microphone, a half-inch condenser microphone Brüel & Kjaer type 4165, was recorded on a tape recorder, Nagra IV-SJ. The tape recordings were then analyzed in a frequency analyzer, Nicolet dual channel FFT-analyzer 660B as average RMS-spectra in third-octave bands. The dB(A)-level was determined with Brüel and Kjaer digital frequency analyzer 2131.

The results are presented in figure 15 as third-octave frequency spectra and dB(A) levels.

First examining the spectra 0-50 kHz one notices, that the noise coming from the drill steel is high-frequency with a maximum in the range 5-20 kHz. In this range the difference between natural rubber and Adiprene is negligible. The steel holder gives a 2-3 dB higher level. This is also reflected in the dB(A) levels for the three materials.

Turning to the spectra 0-5 kHz one notices again similarities in the three spectra in the upper part of the frequency range, 250-5000 Hz. For lower frequencies however there is
a difference in amplitude. This is especially obvious for the third-octave band with 25 Hz as the center frequency. The level for the steel holder is there 84 dB, while the corresponding values for Adiprene and rubber are 76 dB and 71 dB. This result shows that the lower modes of the flexural waves are more effectively damped than higher modes. Unfortunately this difference in the lower part of the frequency spectrum gives a very small difference in the dB(A)-value. The reason for this is that the human ear is less sensitive to low frequency noise, and the measured values in this part of the spectrum are considerably reduced when calculating the dB(A)-value. For example the level for the octave-band with centre frequency at 63 Hz is reduced with 26 dB.
Figure 15:  a) Rubber holder 0-5 kHz
           b) Rubber holder 0-50 kHz

Weighted noise level: 97 dB(A)
Figure 15:  
c) Adiprene holder 0-5 kHz  
d) Adiprene holder 0-50 kHz

Weighted noise level: 98 dB(A)
Weighted noise level: 100.5 dB(A)

Figure 15:  
e) Steel holder 0-5 kHz  
f) Steel holder 0-50 kHz
5. Conclusions

In principal two types of waves can be responsible for the noise production in a drill steel, the longitudinal and the flexural wave. The longitudinal wave acts as an acoustic source due to dilatation of the rod. The flexural wave acts as an acoustic dipole. It is well known (7) that the acoustic source is a more efficient radiator than the dipole. It is however much less energy consuming to flex the rod than to dilatate it. As a result of this, the amplitude of the flexural wave can far exceed the amplitude of the longitudinal wave. Consequently the flexural wave can give a major contribution to the emitted noise.

If one considers the present design of the holder of the drill steel, it is clear, that the object of the designer is to put as much as possible of the striking energy from the hammer in to the longitudinal pulse. These efforts will minimize possible outgoing flexural waves. The necessary clearance between the chuck and the shank of the drill steel makes a complete elimination of flexural waves almost impossible. In (1) it is shown, that other sources for flexural waves are non-symmetric conditions when the wave is reflected off the bit end and propagation of longitudinal waves in a curved rod. These flexural waves will interact with the rod holder, and reflected waves will be produced. The amplitude of these reflected waves will be strongly dependent on the conditions at the holder.
The reason for measuring the dynamic modulus of elasticity and the damping factor for the materials used in this experimental study, was to use them in a numerical simulation of flexural wave motion in a rod. To be able to make comparisons between the numerical and the experimental results, the same method of excitation was used. The results show good agreement for longer periods of time. When comparing the experimental recordings for a period of 2.047 s presented in figure 13 with the numerical results, the same difference in damping is found between the steel holder and the absorbing holder. For shorter times the correspondence between the numerical and the experimental results is not so good. One way to get a closer correspondence could be to make the time step in the numerical calculation smaller.

The results from the short time strain gauge measurements show, that there is a decrease in the amplitude of the reflected wave, when absorbing material is introduced in the holder. The same effect was observed in the photo-elastic model study.

The long time measurements of the strain level show a drastic difference in the damping, expressed as the logarithmic decrement. As the point of excitation is at the free end of the rod, the rod will vibrate mainly in its first resonance mode. One obvious question is, if this damping is fast enough. The frequency for a percussive drilling machine is typically of the order of 50 Hz. This
means that the time between two successive blows is 0.02 s.
A simple calculation shows, that the difference in damping
for one single cycle is considerable. The ratio between
the amplitude for two successive cycles is 0.95 for the
steel holder and 0.64 for the holder with rubber 70° Shore A.
This means that the damping is effective even for a short
time. One has also to be aware of the fact, that the way
the drill rod is excited in our experiment is not the same
as in reality. As stated above the flexural wave in the
drill rod is produced from a longitudinal wave. This means
that the excitation frequency is not the same as the
resonance frequency for flexural waves. Another important
matter is that absorbing material in the holder will prevent
flexural waves from being amplified when reflected off the
holder, and thus retard the build up of flexural resonances.

The noise measurements show a difference between the steel
and the rubber holder of about 3 dB(A). The difference in
the low frequency part of the spectrum is however greater
and for certain frequencies is of the order of 10 dB. This
has a very small effect on the dB(A) value, as the A-
weighting curve takes the sensitivity of the human ear into
consideration.

To transfer these promising results to a new design of the
percussive drilling machine, further work has to be done to
solve possible strength and heating problems that may occur,
with a chuck containing visco-elastic material. This way of
introducing damping is however easier to put into practice, than previous attempts to attach damping materials in or outside the drill steel.
REFERENCES


OBSERVATIONS OF TURBULENT SPOTS ON A WATER TABLE

by

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ABSTRACT

An experimental study of turbulent spots on a water table has been conducted. The Reynolds number, based on the surface speed and the water depth, at which spots first can be generated, is found to be in the range 950–1050. The influence of the Reynolds number and the slope of the water table on the propagation speeds of the front and the rear of the spot and on the half angle of spread has been determined.

A new photographic technique has been used to register structures within the spot. Streaks elongated in the streamwise direction are found to penetrate the spot and it is observed that undulations on the streaks lead to chaotic motions. It is argued that the unsteadiness of the streaks is responsible for the lateral spreading of the spot.

Comparisons with the theory of direct resonant growth of vertical vorticity show that the theory accounts fairly well for the spreading angle of the spot whereas the propagation speeds of the front and the rear are larger than the observed values.

In addition to the spot studies, the properties of the laminar mean flow has been analyzed with a boundary layer type of approximation under the assumption of a regular weir flow at the upstream end of the plate. Experiments show that the water depth approaches the ultimate (parabolic) value faster than what the theory predicts. With the theory, the velocity profile has been calculated for some experimentally relevant cases.
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6 DISCUSSION

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\( \rho \) - density of water

\( g \) - gravity acceleration

\( \nu \) - kinematic viscosity

\( \theta \) - slope of water table

\( q \) - flow rate per unit width of plate

\( h \) - water depth

\( h_0 \) - water depth for parabolic velocity profile \( = (3\nu q / g \sin \theta)^{1/3} \)

\( h_{00} \) - water depth at crest of weir \( = (q^2 / g)^{1/3} \)

\( h^* \) - ultimate water depth in units of \( h_{00} \)

\( U \) - surface velocity (non-dimensional in ch. 4)

\( U_{00} \) - velocity at crest of weir \( = (q q)^{1/3} \)

\( U_* \) - dimensional surface velocity (ch. 4)

\( R \) - Reynolds number based on bulk velocity and water depth \( (=q/\nu) \)

\( \text{Re} \) - Reynolds number based on surface velocity and water depth
\( (=1.5q/\nu \text{ for parabolic profile}) \)

\( F \) - Froudes number \( (F^2 = U_{00}^2 / h_{00} \sin \theta) \)

\( x_* \) - dimensional distance from crest of weir

\( x \) - non-dimensional distance from weir \( (=x_* / h_{00}) \)

\( u \) - streamwise velocity

\( v \) - velocity normal to plate

\( \psi \) - stream function
1 INTRODUCTION

The flow of a thin layer of liquid down an inclined plane is of considerable interest in a variety of situations. The application of emulsions on film and the use in heat exchangers may serve as technical examples. In everyday life this type of flow can be found e.g. in the windows of plant shops and on a sloping street during a rainfall. In the laboratory the flow has been widely used to simulate supersonic flow around bodies. This is possible since there is a direct mathematical analogy between the shallow water equations and the supersonic flow of an ideal gas (see e.g. Stoker, 1957, p. 25, for a derivation).

Experiments have shown that the flow is subject to a couple of instabilities which set in at different values of the three parameters which describe the flow, i.e. the Reynolds, the Froudes and the Weber numbers. The first instability is basically due to gravity and results in roll-waves easily visible on sloped asphalt streets during heavy rains. The second instability is due to the presence of shear in the flow and leads to the formation of turbulent spots, first observed by Emmons (1951) and often named after him. These spots have had a profound impact on the general view of how turbulence is generated and propagates in wall bounded shear flows. Emmons found that the spot grows linearly in both its spanwise and streamwise dimensions as it travels downstream. Thus its shape is preserved but it will eventually make the whole width of the water table contain turbulent flow. Mitchener (1954) measured the propagation speeds of the rear and the front of the spots as well as its lateral spreading. Relative
to the bulk velocity, the leading and the trailing edges were found to travel at velocities of 0.92 and 0.82, respectively. The half angle of lateral spread was found to be about 6.6 degrees. Measurements were also made in a laminar boundary layer where turbulent spots with a different shape than those on a water table were observed. Considerable effort has since been devoted to the study of boundary layer spots notably by Schubauer & Klebanoff (1955), Elder (1961), Wygnanski et al. (1976), Cantwell et al. (1978), Wygnanski et al. (1979) and Gad-el-hak & Blackwelder (1981). Packets of turbulent flow have also been found in pipe flow (Lindgren, 1957 and Wygnanski, 1977) and in plane Poiseuille flow. In the latter case the spots are associated with a distinct three-dimensional wave pattern (Carlson et al., 1981).

Later studies of turbulent spots on a water table have been directed mostly to the effects of polymer additives (Tanner, 1971, Bertschy, 1979 and Chin, 1981). Long-chained molecules such as poly-ethyleneoxide (Polyox) have been found to quench the spanwise growth of the spots thereby delaying the appearance of fully developed turbulent flow. This reduces considerably the frictional drag of the surface, an effect observed in pipes and plates as well. However, the use of polymers as drag reducing agents has not been commercially adopted on any larger scale because of the high costs involved. Therefore, other means of reducing the drag have been considered; one possibility being to structure the surface in such a way that the turbulence generation process close to the wall will be negatively affected.

In order to investigate the effects of structured surfaces on the generation of turbulent spots (and thereby turbulence) a
water table has been built at the Department of Mechanical Engineering at the University of Luleå. In this report a first series of measurements of flow properties and turbulent spots will be reported upon. Later, the effects of structured surfaces on the formation and propagation of spots will be reported as well as an account for the stability properties of the flow. The stability studies are analytical and numerical and are conducted in parallel with the experimental program.
EXPERIMENTAL SETUP

The flow system used in the experiments is shown in figure 2.1. Water is pumped from the lower tank through two parallel filters via a venturimeter to the upper tank. The flow from the pump can be shunted back to the lower tank. Together with a valve on the main line, this serves as the flow rate adjustment. As a critical water level is reached in the upper tank, water starts to flow down the glass plate. At the end of the plate is mounted a sheet of rubber to avoid leakage to the floor. It is also used to collect water for the calibration of the venturimeter. The total volume of water is about 1.25 cubic meters.

The glass plate is made of regular float glass and has the dimensions 6*806*2000 mm. At its upstream end it is joined smoothly to a curved aluminium plate which serves as a contraction. On the sides of the sheet are attached vertical plates which have rounded vertical edges to eliminate strong vortex formation. The fundament which supports the glass plate is connected to the upper tank with two pins around which pivoting is possible. The slope of the water table is set by a jack located 50 cm from the downstream end of the plate. The angle is indicated with a laser beam on a scale attached to the wall 3500 mm from the pivot point. The readings of the scale are accurate to within .02 degrees. Horizontalization of the plate is done with a high precision water-level. The sideways tilt is eliminated by adjusting the tilt of the upper tank.

The flow rate is determined from the pressure drop over the venturimeter. A differential pressure transducer, calibrated with a regular manometer, measures the pressure and the value is
displayed both in digital and analogous form. Elementary theory for the venturimeter (see e.g. Kay & Nedderman, p. 23) shows that the flow rate is proportional to the square root of the pressure. The constant of proportionality was determined by collecting and weighing the flow passing over the plate. It was found to be $1.05 \times 10^{-3}$ if the pressure is given in meters of water head and the flow rate in $m^3/s$.

The thickness of the water layer is measured with a micrometer on which is attached a sharp needle to make the contact with the free surface well defined. A slight tap on the micrometer is used to determine when the needle is in contact with the glass surface. A set-square is used to adjust the axis of the micrometer vertically to the plate.

The temperature of the water is measured to within $\pm 0.1°C$ with a regular thermometer. During an experimental session the temperature increases only slowly but can change from day to day depending on the room temperature. No effort was made to control the temperature. The fluid parameter most sensitive to variations in temperature is the viscosity. It was measured with a Höppler viscometer at sample temperatures and the change with temperature was taken from standard tables (see e.g. Batchelor, 1967, p. 597).
3 MEASUREMENTS OF MEAN FLOW QUANTITIES

When expressing the observations of turbulent spots in non-dimensional units, it is necessary to know the properties of the mean flow quite accurately. When forming the Reynolds number, the flow rate, the water depth and the viscosity must be known. For the determination of the propagation speeds of the spot, the surface speed must also be known. It is customary for this kind of flow to use the bulk velocity, i.e. flow rate per unit width divided by the water depth, as the characteristic speed. The Reynolds number based on the water depth is then a constant along the plate. However, in the treatment of the stability of the flow the surface velocity is used. When the mean flow has obtained the parabolic profile, the two velocities are related through a factor of 1.5. The downstream distance needed to obtain this profile increases with the flow rate and with a decrease in the slope of the water table. An indirect means of assessing the parabolic character of the velocity profile is to measure the water depth and compare it with the theoretical value

$$h_0 = \left(\frac{3vq}{gsin\theta}\right)^{1/3}$$

(3.1)

which is obtained from the Navier-Stokes' equations under the assumption of no streamwise variation of the mean flow.

In this chapter are presented measurements of the water depth as a function of the flow rate for two downstream positions. These are located at the point where spots were generated i.e. at 1051 mm from the end of the plate, and at a point 169 mm from the end. Measurements of the height variation with downstream
distance were also conducted. These will be presented in the next chapter together with an analysis of the developing mean flow, based on the boundary layer approximation.

Another indirect way of determining the parabolic character of the flow is to measure the speed of the free surface. This was done on the lower half of the plate using circular pieces of white paper as markers, produced with a standard office hole-punch. The markers were introduced to the surface in the slow flow of the upper tank and their motion was recorded with a video camera. The velocity was obtained by measuring the time the marker travelled a certain distance and the velocity obtained is thus the average of the surface speed in the interval. Despite the somewhat crude resolution of the video output, the velocities of different markers were found to have very small variation. The results will be presented in the second paragraph. A comparison with the "parabolic" result

\[ U = 1.5q/h \quad (3.2) \]

is also made.

3.1 The water depth as a function of flow rate

The water depth was measured as a function of flow rate at two positions, 169 and 1051 mm from the downstream end of the plate. For each position, two slopes, 1° and 3°, were used. The results for the two angles are shown in figures 3.1a-b, respectively, where the water depth versus flow rate per unit width is plotted. In the figures, the solid curve represents values ob-
tained with (3.1). For each angle the temperature varied slightly between the two sets of points. The viscosity used in (3.1) is the average of the values for the two temperatures indicated. The accuracy of the water depth measurements is ±0.02 mm in which is not included the effects of the ever-present wave pattern caused by the non-uniform wetting of the side walls. The amplitude of these waves increased with the flow rate. Also, as the flow rate decreased, the surface became unsteady with the largest amplitudes occurring at the end of the plate. At the largest flow rates turbulent spots were spontaneously generated. During the passage of a spot past the measuring station, the water depth was increased followed by a decrease and then a subsequent increase back to the original depth.

The figures show that, at the far downstream point, the water depth is very close to the theoretical constant-height value for flow rates lower than .001 m²/s. This break-point value increases with the angle. At the upstream point the water depth never attains the asymptotic value. It is seen that straight lines can be drawn through the data points to a high degree of accuracy. There is no theoretical justification for this; it may just be an effect of the finite flow rate interval. Nevertheless, this observation can be used to estimate the water depth in intermediate points.

3.2 Measurements of the surface speed

The surface speed measurements were done in the third quarter of the plate i.e. downstream the point where spots were generated. The video recordings of the passing markers were displayed frame
by frame and the number of frames, each corresponding to 0.04 sec, for the travelling of a given distance was counted. The resolution obtained with this technique was limited by the inaccuracy in the determination of the position of the marker on the TV-monitor. As large a number of frames as possible were therefore used. In addition to the velocity measurements, the water depth at about the mid-point (828.5 mm from the downstream end) of the interval was also determined. The data obtained are summarized in table 3.1. In the table are also given the surface speed for a parabolic profile calculated from (3.2). A comparison with the measured values show a surprisingly good agreement which indicates that the velocity profile is nearly parabolic even when the height has not attained its final value. On basis of these results, (3.2) was used for the determination of the surface speed. The maximum error is then less than about 2%.

<table>
<thead>
<tr>
<th>$\theta^\circ$</th>
<th>$T^\circ C$</th>
<th>$q \cdot 10^3$ ($m^2/s$)</th>
<th>Surface vel. (m/s)</th>
<th>$\frac{3}{2} \frac{G}{h}$</th>
<th>h (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.5</td>
<td>0.906</td>
<td>0.532 ($\pm$0.015)</td>
<td>0.523</td>
<td>2.60</td>
</tr>
<tr>
<td>3</td>
<td>21.7</td>
<td>0.906</td>
<td>0.780 ($\pm$0.005)</td>
<td>0.768</td>
<td>1.77</td>
</tr>
<tr>
<td>3</td>
<td>21.7</td>
<td>1.228</td>
<td>0.926 ($\pm$0.015)</td>
<td>0.926</td>
<td>1.99</td>
</tr>
</tbody>
</table>

(±0.02)

Table 3.1: Surface velocities obtained from video recordings. h is measured 828.5 mm from the downstream end of the plate.
3.3 Determination of surface speed from height measurements and determination of Reynolds number

Spot observations were done only on the lower half of the glass plate. When relating the spot propagation speeds to the surface velocity, the variation of the latter with downstream distance must be accounted for. As will be shown in chapter 5, the spot velocities are measurably constant along the test section. It is therefore reasonable to relate these velocities to the surface speed in the middle of the interval of observation i.e. at about 750 mm from the downstream end of the plate. Since the variation in water depth is slow in this region, the water depth at the mid-point can be calculated as the average of the depths measured upstream and downstream of the point. Using the so obtained depth gave then the surface velocity via (3.2).

The good agreement between measured surface velocities and those calculated from (3.2) also indicates that a good approximation for the Reynolds number, based on the surface velocity, is given by

\[ \text{Re} = 1.5 \frac{q}{v}. \]  

(3.3)
4 DEVELOPMENT OF THE MEAN FLOW

4.1 Theoretical considerations

The water table flow may be considered as a weir flow which eventually, due to the effects of viscosity and gravity, develops into a flow with a parabolic velocity profile and with a constant water depth. In the simplest analysis of weir flow (see e.g. Batchelor, 1967, p. 391) viscosity is not considered and the velocity is assumed to be uniform throughout the liquid layer. At the crest of the weir the velocity is given by

\[ U_{00} = (gq)^{1/3} \]  \hspace{1cm} (4.1)

and the height by

\[ h_{00} = \left( \frac{q^2}{g} \right)^{1/3}. \]  \hspace{1cm} (4.2)

The subsequent development of the flow is that of a boundary layer growth at the solid surface with an accelerating outer flow. Eventually the thinning of the layer due to gravity acceleration is balanced by the boundary layer growth. Before the viscous effects have penetrated to the free surface, the flow may be thought of as a boundary layer with a free stream accelerating according to Bernoulli's equation. If \( x_* \) is the (dimensional) distance downstream from the weir and \( \Theta \) is the slope of the plate, the (dimensional) surface velocity at \( x_* \) is given by

\[ U_* = \sqrt{U_{00}^2 + 2g x_* \sin \Theta} \]  \hspace{1cm} (4.3)
This is the leading order expression which does not take account of the change in water depth. Rather, the water depth can be calculated as $q/U_\ast$.

By introducing $U_{00}$ and $h_{00}$ as velocity and length scales, respectively, equation (4.3) becomes

$$U = \sqrt{1 + \frac{2x}{F^2}}$$

(4.4)

where $F^2 = \frac{U_{00}^2}{gh_{00}}\sin\theta$ is the Froude number.

Upon analyzing the development of the mean flow the boundary layer approximation is used, i.e. streamwise variations are negligible to those normal to the plate (y-direction). The non-dimensional equations that govern the flow are then

$$\begin{align*}
\frac{uu_x + vu_y}{1/F^2} + \frac{1}{R} u_{yy} &= 0 \\

u_x + v_y &= 0
\end{align*}$$

(4.5)

(4.6)

where $u$ and $v$ are the velocity components in the x- and y-directions, respectively. $R$ is the Reynolds number defined as

$$R = \frac{q}{v}$$

(4.7)

where $q$ is the flow rate per unit width and $v$ is the kinematic viscosity.

The boundary conditions are

$$\begin{align*}
\begin{cases}
    u = v = 0 & \text{at } y = 0 \\
    u_y = 0 & y = h(x) \\
    v = uh_x
\end{cases}
\end{align*}$$

(4.8), (4.9), (4.10), (4.11)
Equation (4.5) is the momentum equation in the streamwise direction and (4.6) is the continuity relation. (4.8) and (4.9) are the no-slip and zero normal flux conditions, respectively. (4.10) is the zero stress condition on the free surface and (4.11) defines the free surface. This can also be expressed in terms of a stream function, \( \psi \), for which (4.11) becomes

\[
\psi = 1 \quad \text{at} \quad y = h(x) \quad \text{(4.12)}
\]

In terms of the stream function, the velocities are given by

\[
u = \psi_y \quad \text{and} \quad v = -\psi_x
\]

and the above system reduces to

\[
\psi_y \psi_y - \psi_x \psi_y = \frac{1}{F^2} + \frac{1}{R^\psi y y}
\]

with

\[
\begin{align*}
\psi_x &= \psi_y = 0 \quad \text{at} \quad y = 0 \\
\psi_{yy} &= 0 \quad \text{at} \quad y = h(x)
\end{align*}
\]

A solution to this system can be obtained with the following self-similar type of transformation
\[ \psi = \frac{F}{\sqrt{R}} \xi^{3/4} f(\eta), \quad (4.13) \]
\[ \eta = \frac{\sqrt{R}}{F} \xi^{-1/4} y, \quad (4.14) \]

where
\[ \xi = 1 + \frac{2x}{F^2}. \quad (4.15) \]

In terms of these variables the problem is restated as

\[ f'' + 1.5 * f f' + 1 - f'^2 = 0 \quad (4.16) \]

with
\[ f = f' = 0 \text{ at } \eta = 0, \quad (4.17),(4.18) \]

and
\[ f'' = 0 \quad \left\{ \begin{array}{l} \text{at } \eta = \eta_0. \\ \frac{F}{\sqrt{R}} \xi^{3/4} f = 1 \end{array} \right\} \quad (4.19),(4.20) \]

Since equation (4.16) is of third order and there are four conditions (4.17-4.20), it is possible to determine \( \eta_0 \) as a function of \( F, R \) and \( \xi \). This is done in the following inverse way: First a value of \( f''(0) \) is chosen. This must be in the range
\[ 1.272 \geq f''(0) > 0, \]
where the maximum value is that for a Falkner-Skan profile with \( m = 1/2 \) (see e.g. Schlichting, 1979, p. 154).

Second, equation (4.16) is integrated outwards until \( f'' = 0 \). This
C15

gives \( \eta_0 \) and \( f(\eta_0) \). Third, (4.20) determines \( \xi \) as a function of \( F \) and \( R \) and finally the height is given by (4.14).

The procedure was implemented numerically using a three-step Adams extrapolation method, with a Taylor series expansion at \( \eta = 0 \), for solving (4.16). The results of the calculations are shown in figure 4.1, where \( f'' \) at \( \eta = 0 \) and \( f(\eta_0) \) are plotted versus \( \eta_0 \). In the figure are also shown asymptotic results. For small values of \( \eta_0 \) these are obtained from a series expansion of \( f \) at \( \eta = 0 \) and for large values they are the Falkner-Skan results.

The velocity profile which can be obtained with the method outlined above has been calculated in a couple of cases. These represent two extremes: the first is for \( \theta = 1^\circ, Re = 2000 \) and the second is for \( \theta = 3^\circ, Re = 1000 \). The results are shown in figures 4.2a) and 4.2b), respectively, where for each case the velocity profile has been determined at midplate and at the end of the plate. It is observed that the deviation from the parabolic profile is fairly small. Since measurements show (see below) that the water depth approaches the parabolic value faster than what the theory predicts it is expected that the calculated velocity profiles are conservative estimates of the actual profiles, i.e. the real profiles are closer to parabolic than the calculated ones.

4.2 Water depth measurements

In order to test the applicability of the theory, the water depth was measured at a series of downstream locations from the weir. The results of the measurements are shown in figure 4.3. The
water depth has been normalized with respect to the ultimate water depth. The length scale used is

$$\zeta = \frac{2x}{Rh_+} + h_+^2/3,$$

where $h_+$ is the ultimate water depth expressed in terms of $h_{00}$. In the figure are also plotted the results obtained with the theory, both exactly and asymptotically.

It is seen that the measured values are consistently lower than the theoretical ones. One obvious reason for the discrepancy is that the streamwise location where weir flow is assumed is not given correctly. A difference in this parameter would shift the data points horizontally, only, and this would not explain the vertical shift necessary to make experiments and theory to agree. This is probably because the conditions at the weir are not that of a uniform profile. The boundary layer correction at the weir is therefore not negligible and the flow is not exactly representable in the family of solutions given by (4.16). A more careful analysis of the problem would require these conditions to be known. (In a recent work, Chin 1981, has calculated numerically the water depth for different initial velocity profiles and finds, among other things, that a linear profile gives the smallest values.) However, the difference between the theoretical and the experimental values is less than 10% which indicates that this theory may provide a first, although rough, estimate of the water depth.
OBSERVATIONS OF TURBULENT SPOTS

5.1 Occurrence and generation of spots

When the flow rate exceeds a certain value turbulent spots are spontaneously generated on the water table. They first appear at the side walls but at slightly higher flow rates they may also be formed anywhere on the plate. In that case their precursors are longitudinal streaks which extend over the weir. The breakup of the streaks occurs randomly on the plate. The Reynolds number, given by (3.3), at which spots first occurs is approximately 2200, independent of the slope. This value is apparatus-dependent and is affected by e.g. the wetting of the side walls.

For measuring purposes the naturally occurring spots are of limited value because of the randomness in their generation. When photographing spots it is necessary to know exactly where and when they will occur. Therefore, spots were triggered artificially by means of falling water drops generated with an injection needle. The drops had a diameter of about 2 mm. They could be released from an arbitrary height which had to be increased at small flow rates for spots to form. Also, spots were more difficult to generate at far upstream locations. In all studies of spots the drops impacted the flow at 1051 mm from the downstream end of the plate. For low enough flow rates spots were not possible to generate no matter what the disturbance level was. The flow rate at which spots, generated with a large disturbance, did not decay was found to be almost independent of the slope of the water table. The corresponding Reynolds numbers
are in the range 950-1050. When photographing spots, the flow rate was chosen so that they could be triggered with a reasonable repeatability.

Other means of generating spots were also considered. One way was to make a thin air jet, blown from the injection needle, to hit the water surface. A strong capillary wave pattern was formed by this disturbance but spots were difficult to generate. Only a very strong jet was able to do this. Once a spot was formed it developed in the same manner as drop-generated spots.

As a drop impacts the water, it has a relative velocity, in the streamwise direction, to the free surface. To investigate whether the difference in velocity affects the spot formation, the drop was made to fall through an air stream produced by a fan mounted parallel to the free surface. By changing the velocity of the air stream and the release point of the drop it was possible to make the relative velocity small. By comparing photographs taken with drops having different relative speeds to the free surface no noticeable change in either spot formation or spot structure was observed.

When taking photographs of spots, it was necessary to trigger the light source, an electronic flash lamp, at different times from the drop impact. This was done by directing a laser beam through the water table exactly at the point of drop impact and onto a photo sensitive transistor. At its impact on the surface, the drop thus blocked the beam and the resulting pulse from the photo transistor was fed to a delay unit. The signal from the delay unit then triggered the light source. The distance travelled from the triggering point to the point where the photograph was taken, was determined by simply measuring the position
of the spot relative to lines attached to the bottom side of the glass plate.

5.2 Measurements of spot propagation characteristics

The following spot characteristics were measured: front speed, rear speed and lateral spread as seen from the generation point of the spot. In order to do this as accurately as possible a lighting was required, which made the boundary between the turbulent spot and the laminar flow around it clearly visible. By trying different ways it was found that light incident at a large angle to the normal of the water surface gave the best contrast. The duration of the light pulse from the flash light, around 200 μs, was sufficient for blur in the pictures to be avoided. A 35 mm still camera was placed vertically above the water surface at a distance of about 1 m. After developing and making enlargements the location of the front and rear part of the spot and its lateral spread were determined. A typical sequence is shown in plate I. The position of the rear part of the spot is fairly easy to determine while the front is less defined. (Errors in the determination of the two positions were about ±3.5 mm and ±6.5 mm, respectively.) The positions of the front and the rear of the spots for this series are shown as a function of time in figure 5.1. The slope of the straight lines fitted to the two sets of points gave the corresponding velocities. No systematic deviation from a straight line was observed. By extrapolating the lines to the point where t = 0, it was found that the front seemed always to start downstream and the rear part upstream of the actual generation point. Despite the
relatively large errors involved in the determination of the apparent starting points, it was found that the distance between the front and the rear point was much larger (~10-30 times) than the drop size.

A summary of the obtained propagation speeds and spreading angles, for different slopes and flow rates, is given in table 5.1. The propagation speeds have been normalized with the free surface speed which is obtained through the procedure outlined in chapter 3.

<table>
<thead>
<tr>
<th>$\theta^o$</th>
<th>Re</th>
<th>$u_f/U$</th>
<th>$u_r/U$</th>
<th>$\alpha$($^o$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1110</td>
<td>0.630</td>
<td>0.600</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>1360</td>
<td>0.660</td>
<td>0.597</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>1910</td>
<td>0.665</td>
<td>0.583</td>
<td>7.7</td>
</tr>
<tr>
<td>3</td>
<td>1110</td>
<td>0.592</td>
<td>0.598</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>1360</td>
<td>0.620</td>
<td>0.582</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>1910</td>
<td>0.618</td>
<td>0.582</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Table 5.1: Normalized propagation speeds of front ($f$) and rear ($r$) of turbulent spots, and half angle of spread ($\alpha$).

5.3 Observations of spot structures

In the experiment just described, only limited information of the spot structure can be obtained. However, one observation of some interest is that the wings of the spot have a tendency to break off from the main spot. This tendency was more pronounced
for large slopes and small flow rates and can be seen in some of the spots on plate I (e.g. $t = 1.6\ s$ and $t = 2.0\ s$). However, a complete splitting was never observed.

A disadvantage with the lighting technique used was that the image of the irregularities on the water surface showed preference for certain directions. For example, when the light was incident from the side, structures in the streamwise direction were exaggerated while structures in the spanwise direction were suppressed. A lighting and recording technique was therefore sought which gave no preference to any special structures in the spot. The obvious way to achieve this was to place the light source vertically above the water table with the light incident normal to the water surface. The distance between the light source and the water was about two meters. In front of the light source a narrow slit was mounted and thus the light source could be regarded as a point source. Instead of using a camera as the recording instrument a photographic paper was placed in direct contact with the bottom side of the glass plate. This gave a negative image of the light distribution i.e. more light than that passed through the laminar region gave a higher degree of blackening in the picture. This method has several advantages such as

- It gives a one to one image of the disturbances on the water surface and no distortion is introduced by lenses.
- The resolution is optimal; the grainy structure obtained when making enlargements from a 35 mm negative is avoided.
- The result is obtained almost instantly. The picture is developed and fixed after the exposure and the result can be examined immediately.
Several series of exposures were made with different time delays to study the spot in various stages of its development. Two parameters were varied, the flow rate and the slope of the water table. As the photographic technique is single exposure, the photographs represent different spots. Plate II shows a sequence exposed at a Reynolds number of 1320 and an angle of $3^\circ$. The different time delays are indicated on the plate. Since the Reynolds number is close to that in plate I, a direct comparison of the two methods of registration can be done. It is observed that, with the contact method, much more of an ordered structure emerges, which is dominated by streaks oriented in the streamwise direction. The streaks are seen to extend throughout the length of the spot and they are distorted by irregular structures. These irregularities, which constitute the turbulent part of the spot, make a determination of the streak spacing difficult inside the spot whereas especially at the wings and at the front of the spot a streak spacing can be obtained. For example, in the front of the middle spot the distance between the streaks is about five times the water depth and at the wing of the last spot it is about twice the water depth.

At lower Reynolds numbers than those of plates I and II the shape of the spot may become quite asymmetric with respect to the centre line as evidenced in plate III a,b which show spots at $Re = 1200$ and $\theta = 3^\circ$. The asymmetry, which is probably set up at the impact of the drop, indicates that the spreading of the spot is a matter of destabilizing the wings, a process uninfluenced by the activity at the other wing. This suggests that the spanwise scales of the unstable structures are much smaller than the size of the spot.
For larger Reynolds numbers, see plate IV, the rear part of the spot is rounded off and the irregular structures inside the spot tend to obscure the streakiness observed at lower Reynolds numbers.

As the slope of the water table is decreased, it becomes increasingly difficult to generate spots at a given flow rate. In plate V are shown spots obtained at a Reynolds number of 1375 and the angles 1°, 0.5°, 0.3° and 0.1°, respectively. At the smallest angles, the spot shape is quite irregular but the streakiness is clearly visible. The spots contain large portions of laminar-like flow which is an indication that the streak spacing has increased. This is mainly due to the rescaling caused by the increased water depth.

To obtain information of the time scales involved in the development of the turbulent regions, a video system was used to follow single spots. Although not as distinct, the same streaky structure was observed with this technique as with the contact method. From the recordings, it is clear that the breakdown of the streaks is the mechanism for spanwise growth of the spot. Especially at lower flow rates the oscillations of the streaks and the subsequent breakdown were easy to follow. An example, obtained with the contact method, of periodically distorted streaks is shown in plate IIIc.

The framing speed of the video system was 25 pictures per second which was not sufficient to follow the change in the internal structure of the spot. This sets a lower frequency of 0.04 s\(^{-1}\) of the processes responsible for these changes. To follow the detailed changes within the spot the framing speed must be increased using a high speed camera.
With the video technique was also investigated the effect of a decrease of the surface tension in the drop used to generate the spot. It was found that the shape and the structure of the spot were the same, once it was formed. However, it was more difficult to generate spots. Also, the formation of spots followed a very characteristic sequence: The impacting drop created a disturbance which developed rapidly (< 0.1 sec) into a v-shaped pattern followed by a weaker ring-shaped wave. On this second wave the spots were formed and travelled slower than the ring-wave. This phenomenon is probably due to the finite spreading rate of the surfactant which thus causes an inhomogeneous surface tension. When surfactant was added to the whole body of water, the formation of the spot was seen not to couple to a ring wave and the v-shaped wave was not as distinct as when only the drop contained surfactant.
Since the photographic methods used in the study of spot structures register distortions of the free surface they are not able to detect motions parallel to the plate unless these give rise to distortions normal to the plate. That parallel motions are present in turbulent spots has recently been observed by Fahlgren (1982) who used titanium coated mica particles to visualize the flow in the liquid layer. A streaky pattern was observed, with a streak spacing of about 1.5 water depths, and which moves ahead of the turbulent portion of the spot. In the present experiment, an indication of such a pattern can be seen in the last picture of plate IV.

The longitudinal streaks which have been observed in the present study penetrate the spot and the irregular distortions on them account for the turbulent part of the spot. The streaks are most clearly visible at the wings of the spot and it seems that their instability is responsible for the spanwise spreading of the spot. However, for a disturbance to be transported in the spanwise direction a mechanism must be present to accomplish this. The most likely candidate is wave propagation of shear waves. Despite the large surface deflections observed within the spot, it may be worthwhile to first investigate the options for an explanation offered by linear theory.

Numerical results of Chin (1981) and Gustavsson (1982) both show that Tollmien-Schlichting waves, at Reynolds numbers of interest here, are damped. Unless some kind of secondary instability is invoked, these waves can not alone account for the spreading of the spot.
A linear mechanism which does produce growth in this case is the direct resonance between vertical velocity and vertical vorticity studied by Gustavsson (1982). Four resonances were studied and it was found that, for Reynolds numbers at transition to turbulence and for slopes of the water table of the order of degrees, the resonantly excited structures are highly elongated in the streamwise direction. In Table 6.1 are shown the characteristics of the resonances for $Re = 1000$, $\theta = 3^\circ$ and $\gamma = 3000$, where $\gamma$ is a material parameter which has the given value at a temperature of about $18^\circ C$.

| $\alpha$ | $k$  | $c = c_R + ic_I$             | $1/|ac_I|$ | $\beta/|ac_I|$ |
|---------|------|-----------------------------|------------|---------------|
| 0.07354 | 0.3891 | 0.6718-0.8196i | 16.6       | 6.3           |
| 0.1451  | 5.7970 | 0.6926-0.5750i | 12.0       | 69.5          |
| 0.1314  | 1.0607 | 0.6710-0.9077i | 8.4        | 8.8           |
| 0.4801  | 0.8476 | 0.6991-0.2867i | 7.3        | 5.1           |

Table 6.1: Characteristics of four direct resonances in water table flow; $\alpha$ is the streamwise wave number, $k$ is the modulus of the wave vector, $c$ is the complex phase speed and $\beta$ is the spanwise wave number.

(from Gustavsson, 1982)

From these data the propagation speed in the spanwise direction, $ac_R/\beta$, is found to be 0.13, 0.017, 0.084 and 0.48, respectively, for the four resonances. The corresponding spreading angles, relative to the mean flow direction, are then $10.9^\circ$, $1.4^\circ$, $7.1^\circ$ and $34.5^\circ$.  

For Reynolds number other than 1000 an estimate of the spreading angles can be obtained by assuming the product $aR_e$ to be roughly a constant. Then also $k$ and $c$ are approximately constants. For example, at a Reynolds number of 1400 the spreading angles become $7.8^\circ$, $1.0^\circ$, $5.1^\circ$ and $23.9^\circ$.

Which one of these resonances that will actually be observed in an experiment depends on the spectral contents of the initial disturbance and the growth of each resonance. The resonantly excited waves grow to a maximum amplitude and then decay. From the initial value problem (Gustavsson, 1982) it follows that a relevant measure of the maximum is $\beta/a|c_I|$, where $\beta$ is the spanwise wave number and $c_I$ is the imaginary part of the complex phase speed. For $Re = 1400$ the maxima become approximately 9.0, 97.3, 12.4 and 7.9, respectively. Thus, the relative order of strength of the resonances does not change with the Reynolds number. This indicates that the second resonance would first be observed as the Reynolds number increases, then the third etc. The larger spreading angles that will thus be introduced follow the actual tendency seen in the experiments (cf. table 5.1).

The resonance theory also predicts the distance between wave crests ($= 2\pi/k$) and the phase speeds for the amplified waves. However, the ratio $c_R/|c_I|$ is of the order of unity which indicates that only parts of a full oscillation will be completed before the decay starts. In the experiments, no clearcut evidence is given for the calculated wave lengths to be present although some of the streaks in the spots of plate II are spaced roughly according to the third resonance. The observations of Fahlgren suggest that the second resonance may be present in front of the spot.
Also, the velocities predicted by the theory are seen to be larger than the measured values. This should not be surprising since the spot is actually defined as the area where noticeably large deflections of the free surface are present. These deflections are certainly not describable with a linear theory. However, the experiments of Fahlgren shows that the actual spot is heralded by streaks which do not show up as surface deflections. Thus it is likely that there are components with propagation speeds closer to the theoretical values.

In summary, the theory of direct resonance is seen to account reasonably well for some of the properties of the spots, notably those associated with the front and the wings of the spot. In other words, those parts that travel into a laminar surrounding. Other properties, especially the Reynolds number at which spots can first appear, are not at all predicted. Whether this can be accounted for by the theory must await the treatment of its nonlinear extension.
REFERENCES


ACKNOWLEDGEMENTS

This work has been supported by the National Swedish Board for Technical Development (STU) through the program for hydro-mechanical research.

The authors are indebted to Mr Hans Hansson and Mr Allan Holmgren for their invaluable contributions to the construction of the water table and to Mr Per Gren for assisting in some of the measurements. In addition, Professor Lennart S. Hultgren has contributed to the analysis in chapter 4.
FIGURE CAPTIONS

Figure 2.1: Experimental setup.

Figure 3.1 a) Water depth vs. flow rate for $\theta = 1^\circ$.
   $+$: 1051 mm from downstream end ($t = 22.8^\circ C$)
   $\theta$: 169 "- ($t = 23.2^\circ C$)

b) Water depth vs. flow rate for $\theta = 3^\circ$.
   $+$: as above ($t = 22.2^\circ C$)
   $\theta$: as above ($t = 23.3^\circ C$)

Figure 4.1: $f''(0)$ (I) and $f(\eta_0)$ (II) vs. $\eta_0$.

   a: $\eta_0 (1 - \eta_0^4/24)$; b: $\frac{1}{3} \eta_0^3 (1 - \frac{9}{80} \eta_0^4)$
   c: $\eta_0 - 0.6309$; d: 1.272.

Figure 4.2: Velocity profiles obtained from the solution of
(4.16)-(4.20).

   a) $\theta = 1^\circ$; Re = 2000. I: $x_\ast = 1$ m; II: $x_\ast = 2$ m.
   b) $\theta = 3^\circ$; Re = 1000. I: $x_\ast = 1$ m; II: $x_\ast = 2$ m.

Figure 4.3: Water depth vs. downstream distance.

   $\tilde{h} = h/h_\ast$; $\tilde{z} = 2x/Rh_\ast + h_\ast^2/3$

   ——: exact theory; ----: asymptotic theory

Experiments:

   $\theta$: $R = 1120$, $\theta = 0.53^\circ$; $+$: $R = 1600$, $\theta = 0.53^\circ$
   x: $R = 1120$, $\theta = 3.00^\circ$. (Note: $R$ based on $U_00$ and $h_{00}$)

Figure 5.1: Position of front ($\theta$) and rear (+) of turbulent
spots. $\theta = 3^\circ$; Re = 1360.
Figure 2.1: Experimental setup.
Figure 3.1 a) Water depth vs. flow rate for $\theta=1^\circ$.
+: 1051 mm from downstream end (22.8°C)
$\Theta$: 169 $^\circ$ (23.2°C)
b) Water depth vs. flow rate for $\theta=3^\circ$.
+: see a) (22.2°C)
$\Theta$: see a) (23.3°C).
Figure 4.1: $f''(0)$ (I) and $f(n_0)$ (II) vs. $n_0$.

a: \( n_0(1-n_0^4/24) \); b: \( n_0^3(1-9n_0^4/80)/3 \)
c: \( n_0-0.6309 \); d: 1.272
Figure 4.2: Velocity profiles obtained from (4.16)-(4.20).

a) $\theta=1^\circ$; $Re=2000$. I: $x_*=1m$; II: $x_*=2m$.

b) $\theta=3^\circ$; $Re=1000$.

(The dashed curve is the parabolic profile)
Figure 4.3: Water depth vs. downstream distance.
\[ \tilde{h} = h/h_+; \tilde{\zeta} = 2x/Rh_+h_+^{2/3} \]

---: exact theory; ----: asymptotic theory

Experiments:

@: R = 1120, \( \theta = 0.53^\circ \); +: R = 1600, \( \theta = 0.53^\circ \)

x: R = 1120, \( \theta = 3.00^\circ \). (Note: R based on \( U_{00} \) and \( h_{00} \))
Figure 5.1: Position of front (Θ) and rear (+) of turbulent spots as a function of time. Θ=3° and R=1360.
Plate I: Sequence of spots photographed with camera above and light incident from the side. $\theta=3^\circ$, $Re=1360$ and $h=1.80$ mm.
Plate II: Spots registered with the contact method. Lighting from above and photographic paper under the glass plate.
\( \Theta=3^\circ, \text{Re}=1320 \) and \( h=1.88 \text{ mm} \).
Plate III:

a) and b) Two spots recorded with the same time delay (0.8s) showing non-symmetric growth. Note the tendency of the upper wing in a) to break off from the spot.

c) Pair of distorted streaks in a young spot (0.4s).

( $\theta=3^\circ$, Re=1200)
Plate IV: Sequence showing the growth from a pair of streaks to a fully developed turbulent spot. $\theta=3^\circ, \text{Re}=1820.$
Plate V: Spots generated at different angles. Re=1375.

a) $\theta=1^\circ; t=1.2s; h=2.72\text{mm}$
b) $\theta=0.5^\circ; t=1.4s; h=3.43\text{mm}$
c) $\theta=0.3^\circ; t=2s; h=4.07\text{mm}$
d) $\theta=0.1^\circ; t=6s; h=5.87\text{mm}$
ANALYSIS OF THE FUNDAMENTAL FREQUENCY OF THE HUMAN VOICE AND ITS FREQUENCY DISTRIBUTION BEFORE AND AFTER A VOICE TRAINING PROGRAM.

by

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ABSTRACT

Three groups of test subjects, one with professional voices, one with normal, healthy voices and one with more or less pronounced phonastenic voices took part in an intensive 5-day voice training program. Tape-recordings were made before and after the training period. These tape-recordings were then analyzed with respect to the frequency spectrum of the voice and the fundamental frequency and its variation. Single parameter measures are introduced to describe the different changes. The result shows that it is possible to replace the subjective evaluations now used with objective measures of the effect of a voice training program.
1. INTRODUCTION

Three acoustic parameters that affect the perception of the human voice are periodic and aperiodic components, spectrum of the voice and the fundamental frequency (pitch) and its variation. The assessment of these parameters varies strongly from individual to individual. Comparative studies between evaluations of different voices made by trained people show, that they often come to quite different results. There is therefore a strong need for replacing the subjective type of evaluation with an objective method, where instead of just listening to the voices, one also measures some important variables. The complexity of the human voice makes a heavy demand on the methods and apparatus aiming at a thorough analysis. One must be aware of the fact that our perception of the voice is affected by combinations of different acoustic parameters. Single acoustic measurements can therefore not be expected to give a full description of the voice. Another problem is how the measured data can be compressed in such a way that no essential information is lost.

Kitzing 1979 (1) used the electroglottographic method to determine the fundamental frequency of the voice. Two electrodes are fixed to the neck and a weak alternating current is led through the tissue. The signal across the electrodes will be modulated by the vibrations in the glottis during speech. This modulated signal is recorded on an oscilloscope or a level recorder. Kitzing has with this method determined the normal average fundamental frequency
and the range of the voice for both healthy and pathological voices. Other methods which are based on a direct recording of the vocal folds are the light-glottographic and the ultrasonic glottographic methods.

In this paper we are presenting results from measurements of the fundamental frequency and its variation and the frequency spectrum of three groups of test subjects. The experimental method in this work is based on a real-time frequency analysis of the acoustic signal. The first group consists of a limited number of professional singers, five male and five female, the second group had normal healthy voices, ten male and ten female. The third group of test subjects consists of persons with more or less pronounced phonastenic symptoms, without any disturbances in the vocal folds, and consists of twenty male and twenty female.

All of the test subjects took part in an intensive 5-day training program, which was developed by one of the authors (3). The main idea in this program is to activate the triple organ system contributing to the voice production:

1. The activator formed by the muscles of the abdominal wall, the diaphragm and the thorax.
2. The vibrator, larynx, which is a skeleton of cartilages joined together, containing the vocal folds.
3. The resonator, which comprises the entire supra-glottic pipe, whose cavities resonate the total sound.
Most important in the program is to obtain a deliberate activation of the oblique and transverse abdominal musculature. Measurements made of the bio-electricity generated in these muscles, show a coordination in time and amplitude with the phonation process (4).
2. FUNDAMENTAL FREQUENCY

Measurements

The fundamental frequencies for the different test subjects before and after training were determined in the following way. High-quality audio-tape recordings were made of each test subject reading a standard passage. The passage, a short poem, was chosen to contain as many dark as light vowels. The duration of the passage was about 20 s. The recordings were made before and after the training period.

The speech samples were then analyzed in real time with a 400-channel narrow band frequency analyzer, Brüel and Kjaer 3348.

Fig 1: Measurement of the fundamental frequency.

The experimental set-up.
The analyzer produces a new spectrum every 44.8 ms. To get statistically independent spectra it is necessary to input a new spectrum at intervals equal or greater than \(1/\beta\), where \(\beta = f_u/400\).

In this case the upper frequency limit \(f_u\) was 2000 Hz and hence \(1/\beta = 0.2\) s. This means that five statistically independent spectra can be generated every second, which gives a resolution of 5 Hz. The spectra were read into a computer. As the recorded passage had a duration of about 20 s, each passage resulted in 100 independent spectra. The bandwidth of each of the 400 channels was equal to the resolution 5 Hz. The fundamental frequency was then determined as the frequency with the maximum amplitude within a selected window, see figure 2. The window had three limits, one upper and one lower frequency limit and one lower amplitude limit. The reason for the lower frequency limit was to avoid the low frequency noise coming from the amplifier and the tape recorder being recorded as the fundamental frequency. The reason for the upper frequency limit was to avoid one of the upper formants as the fundamental frequency. It happens sometimes for certain individuals, that the amplitude of the first formant is higher than the fundamental frequency. These upper and lower frequency limits were determined separately for each person from a long time average spectrum of the same passage.

The reason for the lower amplitude limit was to avoid influence of noise during pauses between words and sentences in the speech sample.
Fig 2: Long-time average spectrum with window.

The results were then plotted in a histogram with a class-width of 5 Hz. Two parameters were determined for each spectrum: the fundamental frequency as the arithmetic average of the frequencies for the maximum amplitudes within the window and a measure of variation. The variation was defined as the difference in frequency between the 20th and the 80th percentile. Six examples of histograms are shown in figure 3; a) and b) are recordings from a male test subject in the professional group before and after the training program, c) and d) are recordings from a female test subject in the normal group and e) and f) are from a male test subject in the phonastenic group. The results for all test subjects are summarized in tables I and II and figures 4 and 5.
Fig 3 a) and b): Professional before and after training.
Fig 3 c) and d): Normal before and after training.
Fig 3 e) and f): Phonasthenic before and after training.
Table I. Fundamental frequency

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Table II. Variation in fundamental frequency

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</table>
Fig 4: DIFFERENCE IN FUNDAMENTAL FREQUENCY BEFORE AND AFTER TRAINING.

PROFESSIONAL SINGING TEACHERS

NORMAL

PHONASTENICS
Fig 5: DIFFERENCE IN VARIATION OF THE FUNDAMENTAL FREQUENCY BEFORE AND AFTER TRAINING.

PROFESSIONAL SINGING TEACHERS

NORMAL

PHONASTENICS
Result and Discussion

According to table I it is obvious that all three groups show an increase in their fundamental frequency after one week of training. The increase for the normal and the professional group is about the same, 17 Hz as an average. The increase for the phonastenic group is greater, 24 Hz. This result was expected. The phonastenic voice tend to decrease in intensity due to fatigue, which in turn lowers the pitch of the voice. Generally this training program seems to be effective in bringing the pitch to its optimal range. Kitzing (1) obtained 110 Hz as the fundamental frequency for male and 195 Hz for female both groups with normal, healthy voices. That is in agreement with our results.

The measurements of the variation in fundamental frequency show that the normal and the phonastenic group increased their variation with about 6 Hz corresponding to 21%, while the professional showed a more moderate change, 14%. One reason for the professional group to have a less pronounced increase is the simple fact that even before the training program they were well trained and used their voices in a modulated way. One has also to remember that these measures of change in variation are averages for each of the three groups. Some individuals, especially in the phonastenic group, showed a tremendous change in variation, with an increase from 20 Hz to 55 Hz as an extreme example. Another interesting observation, which can be seen in figure 5, is
that the change in variation shows a large spread for the phonastenic group. Quite many have even decreased their variation after the training period.

A general conclusion of these measurements is that the training program is effective in both raising the pitch and extending the range of the fundamental frequency.
3. LONG-TIME AVERAGE SPECTRUM

Measurements

When listening to test subjects reading the standard passage before and after the training program one can notice a striking difference in the voice quality. In the clinic situation terms like volume, sonority and stability are used to describe this change. However it would be valuable if one could find an objective measure of the change in the voice quality. One such measure could be a comparison of the frequency distribution of the voice before and after the training program. When comparing the frequency spectrum of the human voice with that from for example a musical instrument, one finds that the different harmonics are much less pronounced in the human voice. One reason for this is the form of the human resonator. The resonator consists of several cavities, the larynx, the lower pharynx (the throat), the mouth, the nasal pharynx, the nasal cavities and the sinuses. This resonator has also a unique ability compared with musical instruments to change its shape thereby changing its resonating function. Another factor that will effect the harmonics when making long-time average spectra is that the fundamental frequency will change during the time it takes to get the average. In the long-time average spectra the different harmonics, called formants, can be seen as rather broad peaks.

To find out if there is any systematic change in the frequency spectrum of the voice before and after the treatment
we analyzed the same tape recordings as were used in the determination of the fundamental frequency in a frequency analyzer. The analyzer, the same as in the previous measurements, was set to present the long-time average spectrum of the read passage in the range 0 - 5000 Hz. Here 256 independent spectra, according to a total time of 22.9 s, were used to form the average. Linear averaging in the analyzer was carried out according to the following equation:

\[ A = \frac{1}{K} \sum_{r=1}^{K} T_r \]

where \( A \) is the average level, \( T_r \) is one of the spectra to be averaged, and \( K \) is the number of spectra, in this case 256. Averaging takes place on a channel by channel basis, and the final average formed is a spectrum consisting of the average level in each channel. This mode of averaging is also referred to as ensemble averaging.

A block diagram of the experimental set-up is shown in figure 6.
Fig 6: Long-time average spectrum. The experimental set-up.

The average spectrum was then plotted on a level recorder and also read into the computer.
Result and discussion

Three typical curves, one from each group is shown in figure 7. The first peak corresponds to the fundamental frequency. To correct for differences in microphone distance and amplification between the two recordings, the level of the fundamental before and after treatment were made equal. All three recordings show an increased level of the formants. This increase is especially obvious for frequencies above 1000 Hz. A possible one-parameter measure of this change in the frequency structure is the relation \( a \) between the average intensity above 1000 Hz, \( A_a \), and the average intensity below 1000 Hz, \( A_b \), defined as (2)

\[
\log a = \log A_a - \log A_b
\]

This quantity was calculated after the spectra had been read into the computer. The result as mean values of \( \log a \) is listed in table III. The difference is about the same for all three groups. Another way of presenting the result is shown in figure 8, which is a plot of \( \log a \) before training versus \( \log a \) after training for every test subject. The graph shows that the different test subjects change their \( a \)-values in the same way. This is true for all three groups including the professional. Thus it seems to be possible to estimate the expected \( a \)-value after the training, if the \( a \)-value before the training is determined. In other words it should be possible to decide if the training has been successful or not.
Fig 7: Examples of longtime average spectra before and after training.
   a) Phonastenic. b) Normal. c) Professional.
Fig 8: A plot of log $\alpha$ before the training versus log $\alpha$ after training for the complete material.
REFERENCES


