

Development of Acoustic Measuring Techniques for the Detection of Defects in Sewage Lines

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1. Introduction

The huge amount of monetary resources for maintenance, refurbishment and restoration of defective sewage lines in the future demands the strategic distribution of the available means with respect to a catalogue of priority. To avoid faultive decisions such a catalogue of priority has to be based on a possibly complete description of the condition of the sewage lines and on a prognosis for the development of defects on this basis.

Currently the condition of the sewage line is exclusively assessed on the basis of the inspection by a remotely operated video camera i.e. by the interpretation of the visible surface of the sewage line. The most interesting facts, the important properties of the pipe such as the material integrity of the pipe, the permeability of cracks, the integrity of bell or other connectors for the embedment are not visible. The assessment from video inspection therefore is indirect and is depending on the actual situation, the capacity of the camera and capability and experience of the operator.

Standardisation of defect description by the German Society for Sewage Technology (ATV) in the recommendation Merkblatt 143 could diminish this uncertainty but not remove it. Also several operators found that the catalogue of defect description is insufficient and added descriptive sentences according to their own experience and needs. Thus for a given video picture there is a certain band width and freedom of interpretation, and even misinterpretations will occur.

To overcome this deficiency the German Ministry of Research and Technology (BMFT) released a first part of a research programme with respect to the development of new inspection methods which could be used as a supplement or an alternative to video inspection. The investigation of pipe vibrations as well as the propagation characteristics of reflections and refractions of mechanical waves is the subject of a joint project which is supported in this programme. With respect to the frequency content it is to be distinguished between sound reflection analysis (audible domain from 100 to 10.000 Hz) and ultrasonic analysis (non audible domain from 50.000 to 500.000 Hz).

Whereas in the sound reflection analysis the measurement in the audible frequency domain is based on the experience from the well known sound test of ceramic pipes or other ceramic products, ultrasonic testing is based on methods of non destructive material testing and can furthermore utilise advanced procedures of signal conditioning and signal visualisation of medical diagnostics.

Contrary to the inspection methods by video in both techniques the pipe material of the sewage line is directly examined because the transfer of the induced mechanical waves for vibrations of the pipe material will be investigated.

In a partnership of a sewage line owner (Abwasserverband Saar), a firm of consulting engineers for non destructive dynamic testing (GSP Mannheim), a research institute for ultrasonic testing (FHG IBMT St. Ingbert) an industrial firm for mechanical devices in pipes (Hydac Sulzbach), and an engineering consultant in the field of sewage line and waste water treatment (GKW Mannheim) a testing technique will be developed which allows an improved assessment of condition and also prognosis of the development of defects. The project subdivides according to the specific know how of the partners.

The Abwasserverband Saar was responsible for the total project management and to care for the actual needs of the sewage line operators. For that purpose the AVS constructed a demonstration centre specially designed for the investigation in the capacity of inspections and restoration methods.

The department of ultrasonic testing in the Institute for bio-medical techniques of the Fraunhofer Gesellschaft is developing the method of ultrasonic testing.

The GSP is developing the methods of sound reflection analysis.

The industrial firm Hydac Technology GmbH is constructing prototype tools which allow the application in buried sewage lines according to the design of the developers.

The GWK is providing an interface for commonly used sewage line data basis and thus allows the direct use of the results of the new detection methods for the development of a defect and fault catalogue as well as a priority list for the restoration.

In the following first the development of the acoustic methods for the detection of defects is described and some details of the measuring techniques are shown. After the detailed description of the methods and presentation of results of laboratory and in situ testing the exploitation of the results in a sewage line inspection strategy is presented and the usefulness and design of the sewage line demonstration centre is described.

2. Acoustic measuring techniques

In general the quality and integrity of ceramic products of any kind is assessed by the sound that is heard when the piece is hit by a hard instrument. Ceramic pipes are not only during production subject to a quality control by sound reflection and therefore hit with a metal bar, but also before bringing them into the ground they are hit by the foreman on the site to know whether the integrity is still present. A defect in the pipe will be noticed by different musical pitch or by changed sound characteristics and the length of the sound. Musical pitch is connected with the change in frequency whereas the length of the sound is depending on the damping.

In ceramic industry long time investigations have been carried out to try to find a relationship between the sound pattern, especially the pitch of frequency of an intact pipe and the top load resistance according to Code DIN 1230. This relationship however could be verified in a statistic mean but it showed not to be economical from these results to change to an automatic quality assurance on the basis of sound testing. By the many experiments that have been carried out on pipes of all kinds it could be noticed that the signals gathered from a sound always show a special pattern for intact pipes or special defects (see fig. 1).

With respect to the position of sound testing in the production process of ceramic pipes the sound testing has been carried out on freely vibrating pipes which lie on supports or hanging on cranes where the impact could be applied from the outside. Sound measurements with a microphone during those sound tests showed that intact pipes have characteristic individual eigenvibrations. Those eigenvibrations are different for the individual pipes but when an average is taken for a number of pipes it shows that the eigenfrequencies for a type of pipe and diameter were contained in small frequency bands. It must be distinguished however between pipes hit at the bell connector or hit at the sharp end (see fig. 1).

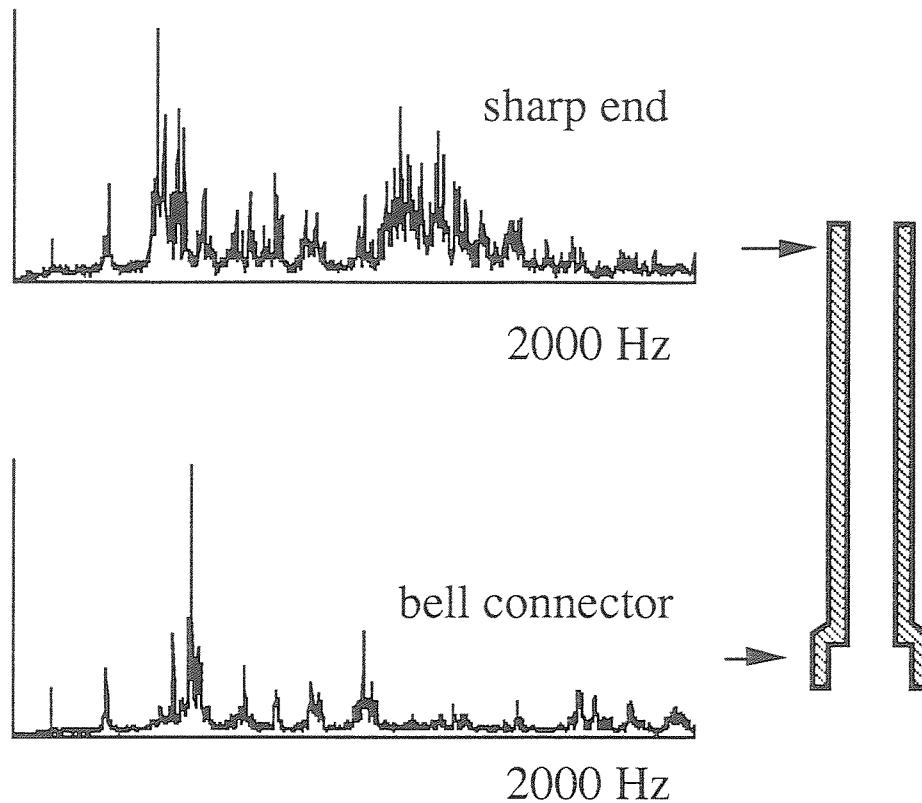


Figure 1 : Frequency averages of sound testing of ceramic pipes of diameter 200 mm

On the basis of these experiences for the transfer of the sound testing during production to a testing method for buried ceramic pipes certain work hypotheses could be taken:

1. A pipe buried in the ground will have characteristic eigenvibrations like a free pipe.
2. Hitting a ceramic pipe will show transient vibrations. These vibrations are composed by their eigenvibrations and therefore the eigenfrequencies can be determined by measurements.
3. A frequency controlled stationary harmonic excitation of the pipes will show eigenfrequencies by resonance.
4. An ambient stochastic excitation which might be a micro-seismicity or a general background noise could be filtered by the eigenfrequencies of the pipe. By measurements of the filtered vibrations the characteristic properties of the pipe can be determined.
5. Differences in the embedment can be determined by different dampings in the signal.

6. A crack in the pipe will prevent the propagation of the induced wave when the pipe is hit so that for a symmetrical measurement set up unsymmetric phase shifted signals will be gained.

For the development of the method for application in inspection of sewage lines the following work programme has been drawn:

1. Basic investigation of excitation of the pipes and measurement of vibrations, determination of signal patterns for pipes and computer simulation of pipe vibrations.
2. Analysis of back ground noise and microseismicity.
3. Design and construction of a prototype for the inspection of inaccessible buried pipes by sound reflection analysis.

The instrumental basis of a signal production by pipe excitation and signal collection have been investigated by measurements in the laboratory. Several methods of excitation including usage of impact hammers have been examined. For the measurement of pipe movements a number of geophones or acceleration transducers of different producers have been used. It showed that a steel hammer with a rounded head that is usually used in craft work of jewellery was best suited as an hitting instrument and generally applied piezoelectric acceleration transducers with a mounted resonance frequency of 20 kHz or more showed best results.

For the confirmation of the measured frequency graphs measurements with a frequency control excitation have been carried out where the frequency range from 0 to 2.000 Hz has been passed in ten minutes. In addition measurements by noise excitations with signal averaging in the frequency domain have been carried out. For freely vibrating pipes lying on a simple support all methods gave the same frequency graphs. So it was assured, that the pipe properties could be completely described.

Furthermore in the laboratory an intact and a cracked pipe segment have been buried in a sandfilled barrel. For the transfer of the excitation and measuring technique to embedded pipes the main difficulties for the application of the method to buried sewage line inspection could be noticed:

1. The embedment is acting that strongly that the free movement of the pipe is suppressed and therefore a stiffened system with a higher basic frequency is generated.
2. The high damping prevents the application of classical instruments of signal analysis because the transient vibrations are very short.

3. Noise excitation and stationary harmonic frequency controlled excitation cannot be applied for embedded pipes, because the coupling of the respective tools are changing the system properties.

From these results it showed, that the working hypothesis 1 that means that there exists a fixed frequency pattern for a given pipe must be dropped in favour of a more fuzzy frequency pattern and the careful analysis of signals in the time domain. The problems with the coupling of frequency controlled excitators restricts the in situ application to impulse or impact excitation.

2.2 Ultrasonic testing

An application of non destructive ultrasonic testing for the localisation and detection of defects in sewage lines is not known by now. On the other hand ultrasonic testing is widely applied in testing of steel pipelines for transport of hydro carbon and especially for crack and corrosion detection in any kind of large steel constructions. The exact measurement of wave propagation velocity and attenuation characteristics provide an assessment of elastic properties and the resolution of the composites of an investigated material with a high resolution. The testing methods are working in the range of the frequency from 500 kHz up to 2 MHz.

Application of ultrasonic testing in engineering construction is not so much applied by now. In testing of structural concrete the relationship between concrete strength and the velocity of sound propagation is known for long but ultrasonic testing as an element of quality control and of routine supervision of safety relevant structural concrete is only applied in few cases. In addition the complex form of poured concrete leads to a very complicated situation of wave propagation within the solid and therefore the interpretation of measurements is always difficult.

A latent problem of ultrasonic testing is arising from the changing of modes that means a change from longitudinal waves to shear waves or the excitation of surface waves. All these wave forms can also be used in a testing method. Recently advanced methods for signal analysis have been developed with a special coupling of the excitation transducers so that surface waves or other disturbances by so called multipath effects can be identified and eliminated.

From the physical background the potential of ultrasonic testing can be seen and therefore the following work hypothesises are given:

1. The sound propagation velocity is a measure for the elastic properties of a body.
2. Attenuation is characterising the absorptive and distributing properties of the investigated material. Especially reflection will always be present at the location of

large changes in acoustic impedance which will be found for instance at cracks.

3. By the measurement of a travel time for a given wave propagation velocity a certain distance, for instance the wall thickness of a pipe can be determined.

The realisation of the physical potential for application of ultrasonic testing in pipes demands a stepwise approximation to the in situ testing conditions. From this a three step approach results:

1. Basing on the known application of ultrasonic testing of structural concrete first the wave propagation in a concrete pipe is investigated. This investigation will result in a technical realisation of different testing techniques. Also in this step different pipe materials like concrete, metal, ceramic, asbestos are examined with respect to their testability, and most appropriate testing methods are determined. From this investigation not only the adequate sensors and transducers will be found but also a computerised set up for a data collection analysis and storage is found.
2. The value and position of ultrasonic test results in buried pipe diagnosis is determined.
3. The findings of step one will be used for the design of a prototype by which in situ investigation are possible.

3. Crack detection

3.1 By sound reflection analysis

By means of a symmetrical set up of measurement and impact tools a direct analysis of a crack is possible in the time domain. In an intact pipe of homogenous material with circular cross section at two symmetrical positions of transducers the signal should be in phase at both transducers. By a crack the wave propagation is interrupted and therefore the transient signal arrives at the position of the transducers at different times (see fig. 2). Because the wave induced by the hammer will take a longer time to travel to that transducer on the opposite side of the crack. This is a direct method of detection.

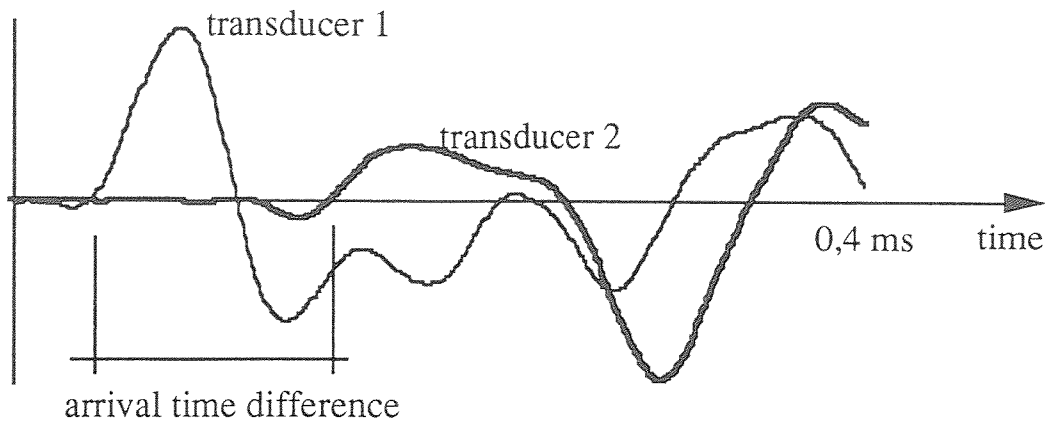


Figure 2a: Crack detection in the time domain by sound reflection analysis

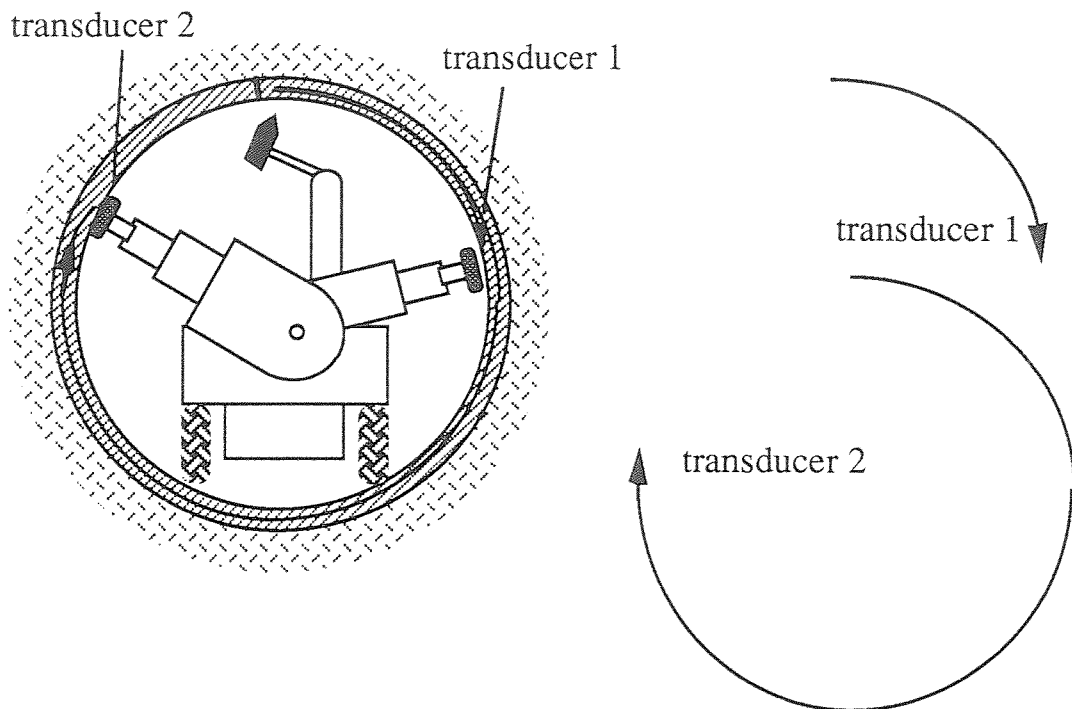


Figure 2b: Crack detection in the time domain by sound reflection analysis

With a peak picker algorithm the analysis of the time histories and the determination of the difference in the arrival times can be carried out automatically.

3.2 Detection of cracks by ultrasonic testing

The crack detection by ultrasonic testing is carried out in a similar way by means of two sensors which are positioned to the inside of the pipe wall. One sensor is producing the signal, the other one is collecting the signal (see fig. 3).

When there is an intact material between the sender and the collector, there will be a good acoustic

coupling and therefore the amplitude of the signal will be nearly constant. By the crack between the two sensors the wave propagation is interrupted and therefore the intensity of the transferred signal will be reduced or will even drop down to zero.

Although this kind of crack detection is straight forward one has to take in mind that for specially confined cracks the development of surface wave, shear waves, and longitudinal waves will be able to disturb the signal at the collector and therefore refined techniques have to be applied to get a unique interpretation.

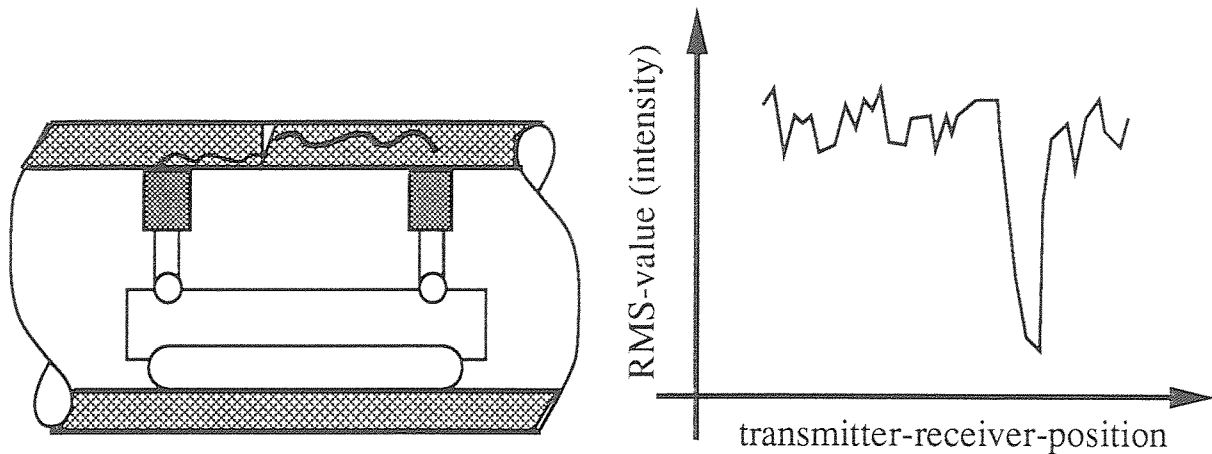


Figure 3 : Crak detection by ultrasonic testing

4. Investigation of connectors

A similar procedure can be applied to flexible connectors of pipes which are usually tightened by the means of elastic material. A complete and tight connection between two pipe segments shows a specified signal transfer. Where the tightening material is interrupted the signal transfer will be reduced. Therefore by moving the collector set up around the surface of the pipe the integrity or tightness of a connector can be determined.

5. Investigation of embedment

5.1 By sound reflection analysis

In a first series of experiments the characteristic frequency patterns for embedded pipes had been investigated in the laboratory by inserting pipes into sandfilled barrels as shown in fig. 4. In this series of experiments also a specially confined embedment has been simulated.

Vibration measurement showed the effect of the embedment very clearly. With respect to a freely vibrating pipe the vibrations of the embedded pipe are damped out very strongly. The vibrations of a partially embedded pipe also show limited damping with damping value between the freely and the totally embedded pipe.

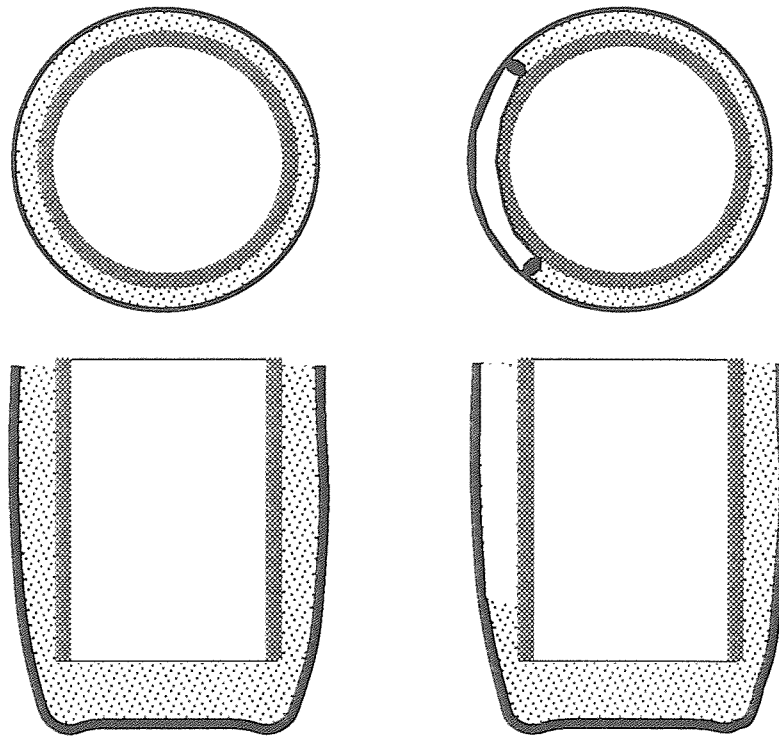


Figure 4: An experimental set up for embedded pipes in the laboratory

The strong damping will prevent the vibrations after an impact to be reproduced for very long time and therefore the frequency analysis is influenced. For the very strongly damped signals of the embedded pipes the prevailing eigenfrequencies are not that sharply shown as in the free vibrating pipe (see fig. 5).

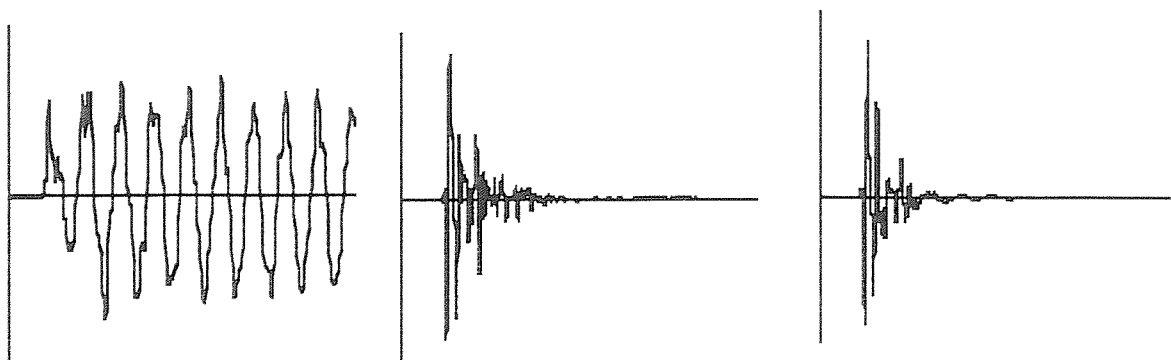


Figure 5: Free vibrating partially embedded and totally embedded pipe,
time histories over 16 ms

In the frequency analysis it can be recognised that the embedment has a stiffening effect on the system "pipe in the ground" because the basic eigenfrequency of the embedded pipe is raised by a factor of 1.2 .

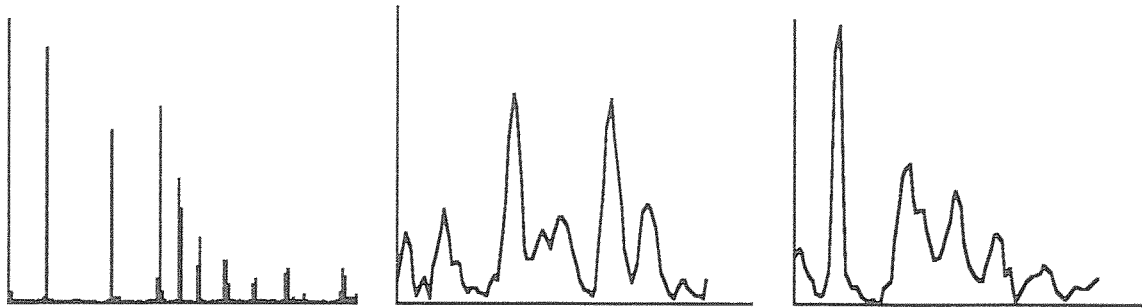


Figure 6: Free vibrating partially embedded and totally embedded pipe frequency analysis for 0 to 5000 Hz

5.2 Investigation of embedment by ultrasonic testing

The backside reflection in ultrasonic testing is in its intensity depending on the change of impedance of pipe to embedding material. If there is a good acoustic contact between the embedment material and the pipe material then the amplitude of the reflected signal is reduced. From preliminary experiments in the laboratory it could be shown that voids in a sand embedment will lead to a raise of intensity of reflection. As has been discussed in the sound reflection analysis the embedment defines the boundary conditions of the eigenmodes of the pipe vibrations. Therefore a possibility is seen that by modal ultrasonic analysis an investigation of the embedment can be carried out. This kind of investigation cannot be done successfully in the laboratory, but must be carried out in suitable test lines.

6. Investigation of wall thickness by ultrasonic testing

By ultrasonic testing the thickness of a wall of a pipe wall can be measured. For this measurement a short signal is induced from the inner surface of the pipe and will be reflected from the other surface. The reflection will arrive at the transducer after the signal has passed the pipe wall from the inside to the outer surface and back to the inside. As the wave propagation velocity for longitudinal waves is larger than for all other wave forms it can be assumed that the first arriving reflection is caused by the back side echo. If the wave propagation velocity is unknown a measurement on the inside can be used to determine it exactly. If the wall thickness is reduced the reflection will arrive earlier at the transducers than for an intact pipe wall.

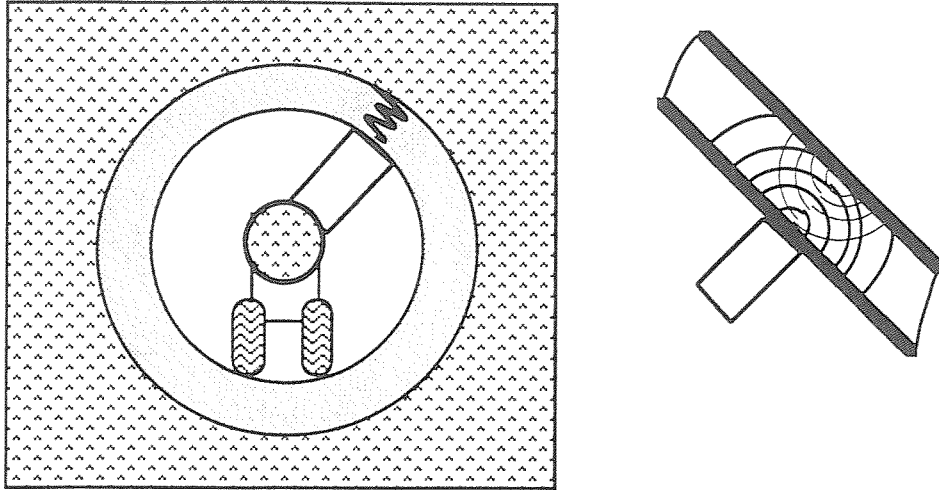


Figure 7 : Determination of wall thickness by ultrasonic impulse echo technique

7. Prototypes for in situ measurement

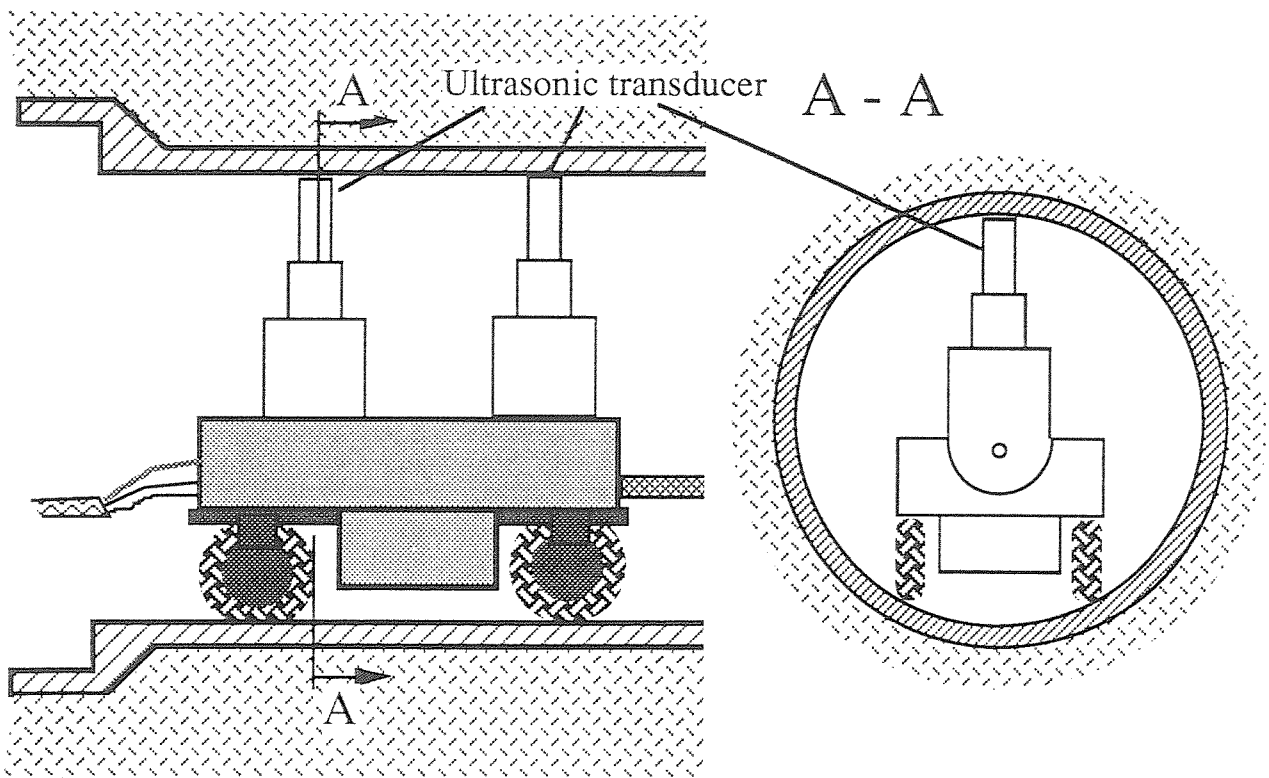


Figure 8: Prototype for ultrasonic in situ testing in sewage lines

Figure 8 shows the prototype for ultrasonic testing according to the experiences gained by the measurements in the laboratory. The set up includes the two ultrasonic transducers at different positions so that sensor and collector can be separately operated. The two sensors can be positioned at arbitrary distances in longitudinal or radial direction.

For sound reflection analysis also a set up with arbitrary positionable transducers and impact hammer would be favourable. But for the first tests only a fixed position of the hammer with symmetrical transducers has been realised. With this position the experiences in crack detection and also in embedment investigation can be gained so that for further prototypes guidelines for design can be developed. With the impactive hammer hitting in orthogonal direction with respect to the acceleration pick ups a separation of signals is guaranteed so that the movement of the carrying construction of the transducers is not interfering with movements of the pipe wall (see fig. 9).

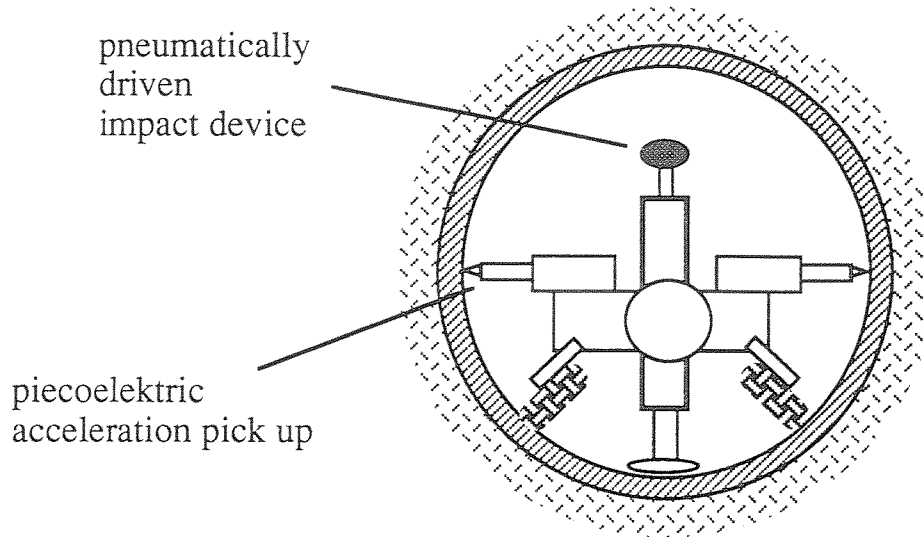


Figure 9 : Prototype for ultrasonic in situ testing in sewage lines

Both prototypes are moved by hand and for correct positioning a video camera is connected to the prototypes for the in situ tests.

8. Sewage line demonstration centre in Burbach

For in situ tests the direct investigation of operated sewage lines was avoided because the prototypes should be electrically covered which is not favourable in a development procedure. Every part should be accessible.

To gather experience with sound reflection analysis first a test sewage line in the yard of Bilfinger + Berger Bauaktiengesellschaft could be used and in a next step newly buried ceramic pipes in the prepared housing area in the city of Mannheim could be used. With these two sewage lines the operability of the prototype for sound reflection analysis could be verified.

After this experiences it showed that for the determination of the capability of the prototypes a sewage line with defined defects would be favourable. Therefore by the Abwasserverband Saar a channel demonstration centre was designed and built. Sewage lines of different materials and

diameters were installed. (See fig. 10.) This demonstration centre is designed to accommodate any kind of testing and inspection tools that are developed within the government programme.

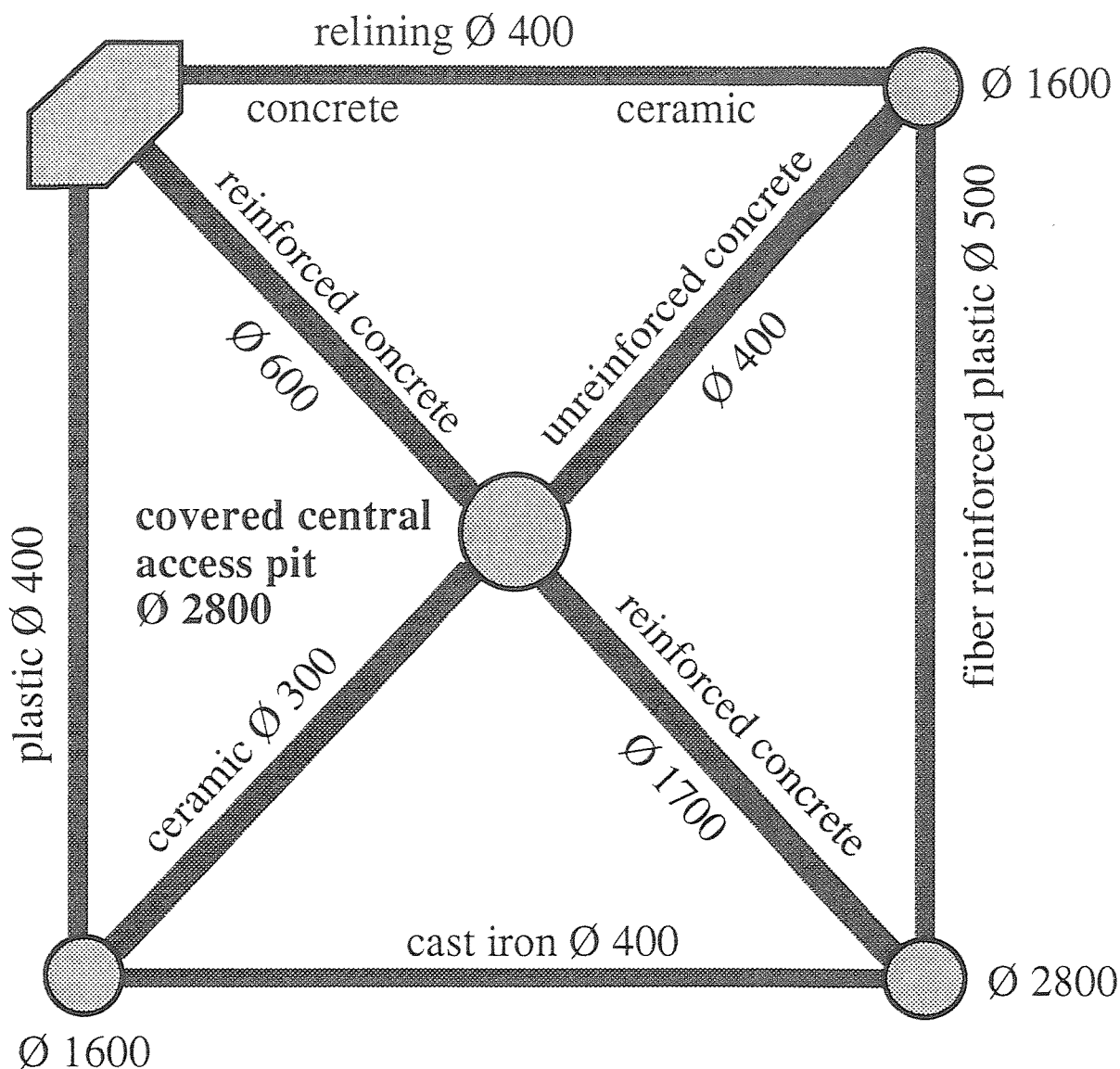


Figure 10 : Sewage line defect detection demonstration centre
of Abwasserverband Saar, AVS, at Burbach

All the lines of different materials have been installed with defects typical for its type.

In fig. 11 the investigation of the ceramic part is shown. The difference of the completely embedded segment and an only partially embedded segment can be recognized in the time domain by the length of a effective signal and in the frequency domain by the presence of higher frequencies. The cracked segment has been found by the difference in the arrival times of the signals at both transducers as has been predicted by laboratory tests.

The investigation of the embedment is evaluated more clearly by drawing a graph of the damping

constant along the axis of the sewage line. The drop in the damping value indicates the position of the reduced embedment (see fig. 12).

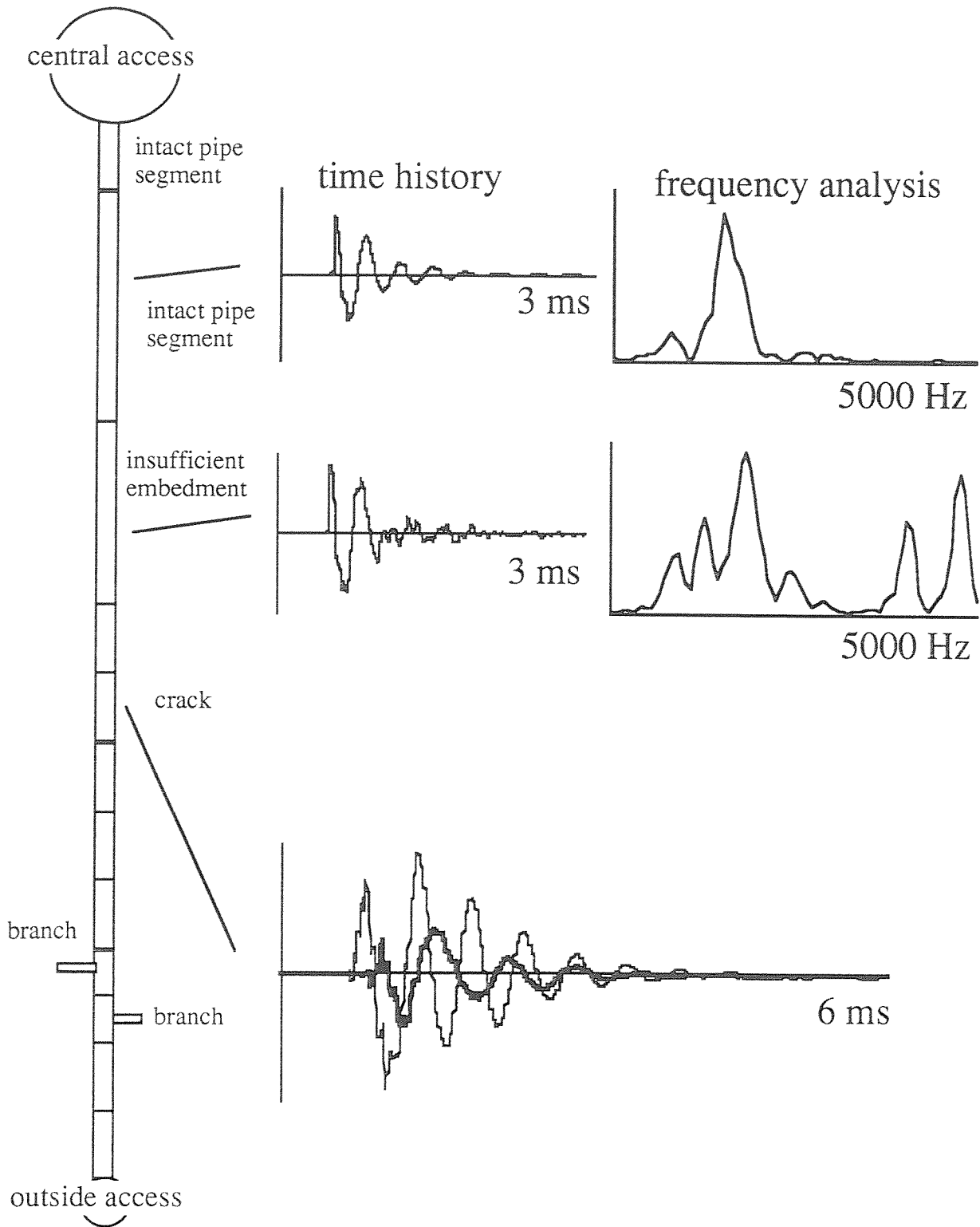


Figure 11 : Fault detection in ceramic sewage line of the demonstration centre

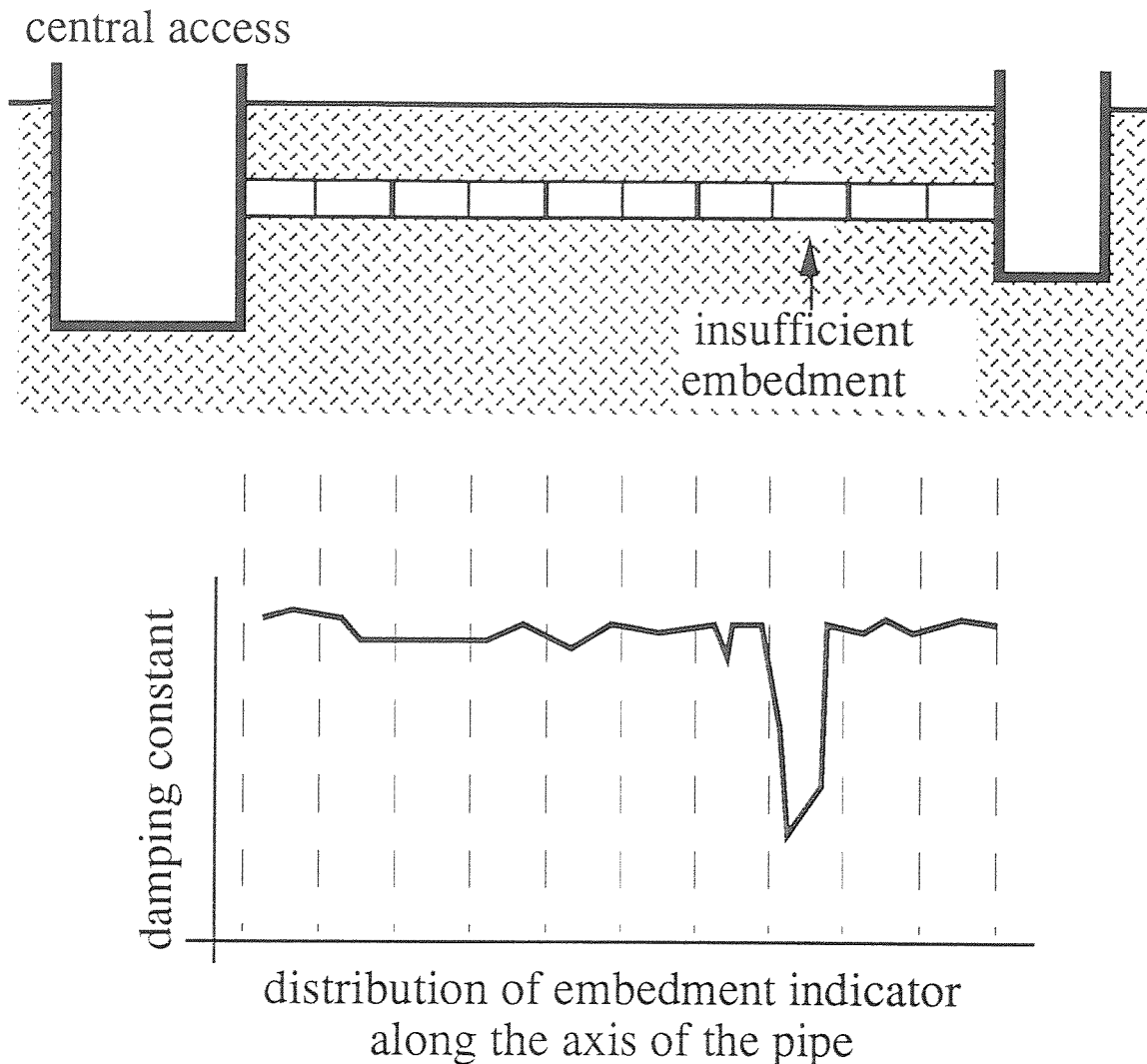


Figure 12 : Embedment control in concrete sewage line of the demonstration centre

9. Utilisation of results in a sewage line data basis and improvement of defect classification.

The now detectable facts are to be implied into a classification system that can be connected with the optically detected defects. On the basis of this information the priority list for restoration and refurbishment can be drawn and the prognoses of defect development can be set out. The situation is visualised by figure 13.

It is recognised that the new inspection method would improve the decision basis for activities within sewage line maintenance. Where other methods of detection are not sufficient now additional methods are available to improve the data basis. Of course costs for information acquisition have to be taken account of. Besides this application as being additional to video inspection the new detection methods show new areas of applicability. First the systematically carried out sound reflection analysis provides signals that can be automatically compared in inspection intervals. On the other hand both inspection techniques can be used for underwater usage

and therefore an investigation of sewage lines and buried channels during operation becomes possible.

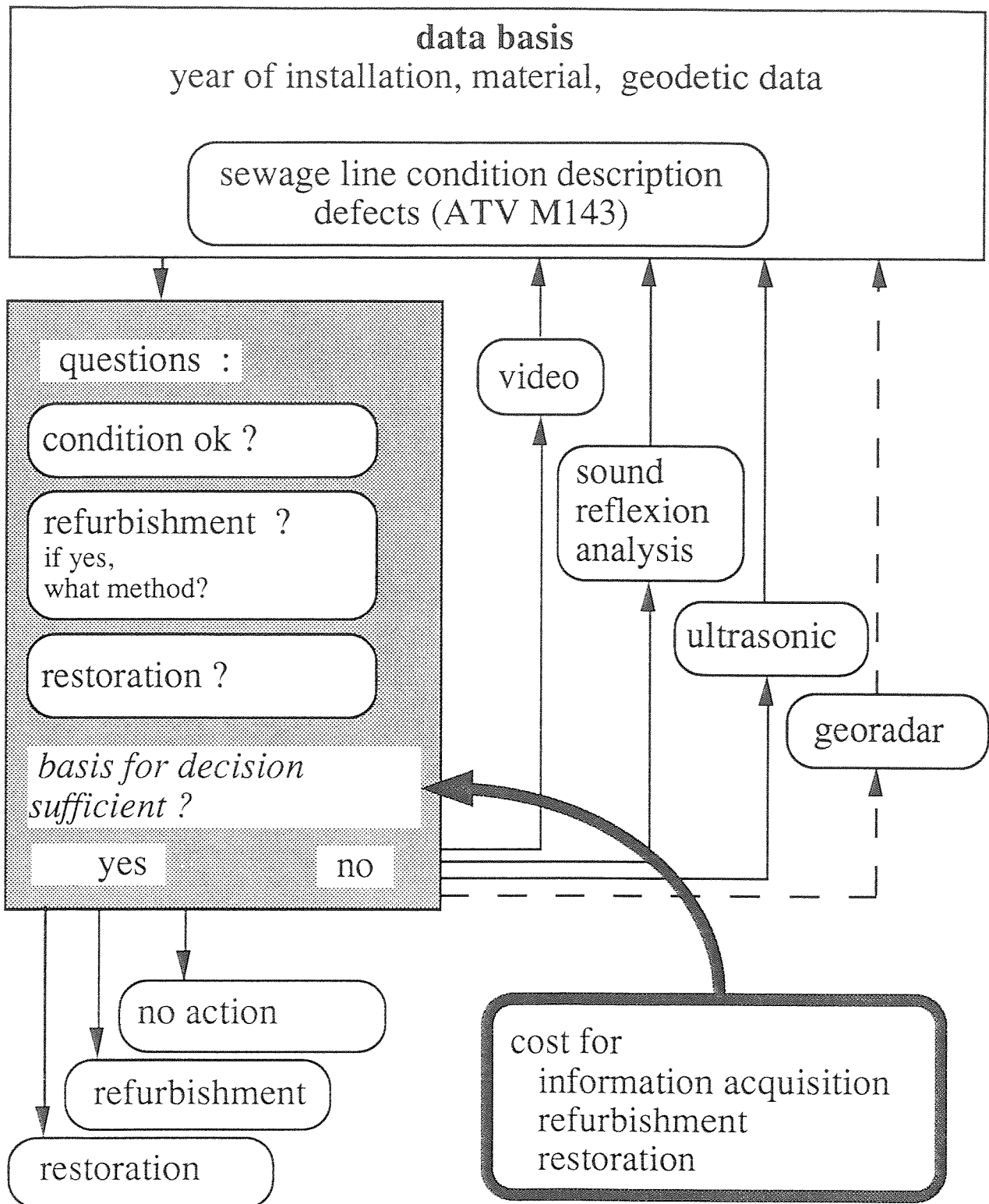


Figure 13 : Utilization of additional information in an expert and knowledge based system

10. Future developments

In addition to the aforementioned decision problem the acoustic detection methods can be favourably utilised in a regular inspection strategy as prescribed by the German "Eigenkontrollverordnung". As the results of acoustic detection can be stored however complex in a very comprehensive form execution of the measurements can be standardised and is reproducible so that an automatic comparison of patterns by computer becomes possible. The changes in the condition of a pipeline can be recognised and the development of defects can be recorded. The automatic regular inspection therefore will save costs without reducing the reliability.

By means of a suitable mechanical enhancement of the prototype the spot oriented ultra-sonic-testing can be improved to an automatic scanning of the inner surface of a pipe. The density of measurement points can be defined either prior to measurement on the basis of expected results or during measurement in an adaptive evaluation of results.

Basically acoustic detection techniques are not depending on a cleared and visible surface and a completely watertight tool will provide an investigation of uncleaned pipelines which are in operation. This kind of inspection will be extremely useful for large collectors or industrial cooling water ducts for permanent processes.

Acknowledgement:

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