MONITORING WOOD DECAY IN POLES BY THE VIBRO-ACOUSTIC RESPONSE METHOD.

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SYNOPSIS

Despite recent advances in the development of new materials, wood continues to be used globally for the support of overhead cable networks used by telecommunications and electrical utility companies. As a natural material, wood is subject to decay and will eventually fail, causing disruption to services and danger to public and company personnel.

The traditional method of testing poles for decay involves hitting them with a hammer and listening to the sound that results. However, evidence suggests that a large number of poles are replaced unnecessarily and a significant number of poles continue to fail unexpectedly in service. Therefore, a more accurate method of assessing the structural integrity of wooden poles is required. The underlying physical principles behind the "pole tester's approach" have been identified and used in the development of a decay meter to enable objective monitoring of decay in wooden poles.

Keywords: Wood decay, wood poles, impact response, acoustic response, condition monitoring.

Nomenclature

E – Young's Modulus (GN/m^2)
G – Modulus of Rigidity (GN/m^2)
I – Second Moment of Area (m^4)
L – Pole Length (m)
m – Pole mass per unit length (kg/m)
x,y,z – Coordinate axis system

ε - strain
ρ - density (kg/m^3)
ν - Poisson's ratio
ω - Natural frequency (rad/sec)
σ - Stress (N/m^2)

1.INTRODUCTION

Wooden poles are widely used by telecommunications and electricity utility companies for the support of overhead cables. Poles have been found to be a relatively cheap and reliable method for supporting an overhead cable network system, are typically 150 - 400 mm in diameter and can range in height up to 10 m or more. Traditionally they are placed vertically in holes, which are drilled into the ground to provide a cantilever type of support.

The tree most commonly used for poles in the UK is the Scots Pine (*Pinus sylvestris),* but other species are used in significant numbers. Wood is a natural, biological material and like all such materials is subject to decay. Decay in wood usually occurs in damp conditions which enable certain fungi to use the wood as a food source. The outer surface of a pole, although usually treated with creosote to prevent moisture ingress, can be attacked by the fungus ascomytes. Such "soft rots" are relatively easily detected by visual inspection and probing and are generally slow to progress to ultimate failure of the pole. However, the internal parts of the pole can be attacked by basidiomycetes fungi, which enter the wood via checks (vertical cracks in the pole that penetrate radially inward), which occur as part of the drying out process. This decay can advance rapidly inside the pole with no external evidence visible to a cursory inspection. Subsequent failure of the pole can occur unexpectedly once the decay has weakened its structural strength sufficiently. The decay is found most often at or near the ground level where moisture conditions are most conducive to fungal growth. Unfortunately this is also the location of greatest bending moment on the pole, which magnifies the effect of the decay.

Replacement of a pole can cost as much as £1000 and it has an average life expectancy of 45 years. The useful life of a pole is affected by many factors, which are largely beyond the control of the utility operators. Variability in the quality of the wood, preservative treatment, site conditions, loading etc. can all lead to unexpected failure of the pole. This can result in serious consequential losses in terms of public/personnel safety and system integrity. To avoid such failures, most utility companies employ "pole testers" whose job it is to inspect poles periodically to decide if they are fit to continue supporting the network until the next inspection is to be undertaken. The frequency of inspections is typically 5 - 7 years. A number of utility companies employ a basic acoustic response testing method to determine the presence of internal decay. The tester strikes the pole with a hammer and listens to the noise that is made. Subjective assessment is then made by the tester as to the severity of any decay present. Surprisingly, this method is reasonably reliable but understandably testers tend to err on the side of caution. It is generally recognised that a

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large number of poles are classified as "defective" when the level of decay is insufficient to warrant their replacement. Such unnecessary replacements are costing utility companies several £millions per year. Over the last 25 years considerable efforts have been made to improve upon existing testing methods and develop a system, which is reliable, portable and inexpensive.

2. PREVIOUS TESTING METHODS

A wide range of technologies have been used in an attempt to produce a pole testing system that is more reliable than the "wheeltapper" approach. The main methods, which are described in the literature or have been developed commercially, are outlined.

2.1 Ultrasonics

Ultrasound is a vibration that is at a frequency which is higher than one in the audible range (> 20 kHz). Usually pulses of ultrasound are directed into the pole in a radial direction. The time for the pulse to travel across the pole is measured. This procedure is usually repeated at a number of locations around the circumference. The waves of ultrasound travel at speeds of approximately 2000 m/s in sound wood and slow down to speeds in the range 1200 – 1500 m/s when passing through or around decayed sections. The time of flight gives an indication of the presence of decayed material. The method was pioneered in the 1980's [1,2] and developed commercially[3]. It has been used successfully on building timbers [4] but has had mixed success on utility poles. The cost of the instrument and the time required to survey a complete pole tend to discourage more widespread use.

2.2 Medical techniques

The location of decay within a pole can be likened to identifying fractures or abnormalities within the human body. It is therefore not surprising to find that techniques, long established in medical investigations, such as X rays, NMR etc. have been applied to locating decay in poles. Little published information could be found on the use of these techniques, presumably because developing a cost effective, safe and portable system would be difficult to implement.

2.3 Electrical impedance

As decay progresses in wood, the fungus breaks down the wood structure converting the lignin to starch and sugar, releasing ions, which change the electrical impedance properties of the wood. Initial trials of a tomographic sensor based on this approach have been described[5] but the accuracy of the system was insufficient for it to be of practical use. It is believed that further work on this system is ongoing.

2.4 CO_2 detection

As well as the production of ions, the decay process results in the production of CO_2. This can be detected by electrochemical sensor instruments and this approach has been studied and evaluated by a number of companies. However, a reliable and cost effective system is yet to be developed.

2.5 Invasive technologies

Probes forced into the pole have been used in a number of ways over the years. It is believed that there is a direct correlation between the wood's resistance to penetration and its strength. Italian researchers [6,7] have provided some scientific basis for this approach and used the method successfully on timbers in historical buildings. The basis of the method is to measure the number of calibrated hammer blows per centimetre of penetration of a specially designed probe. An alternative method uses an instrumented drill[8], which provides a graph of penetration resistance against drill progress. Both methods suffer from the drawback that a number of tests will be needed to survey a complete pole and each penetration provides a new potential site for the initiation of decay.

2.6 Proof loading.

Applying a test load to a pole, which is in excess of the design load, is probably the most direct means of assessing the fitness for purpose of a pole. This approach has been used successfully for testing lampposts [9] and, in theory, could be adapted for wooden poles. However there are two major drawbacks :- 1) Many wooden poles are situated at some distance from roads so vehicles could not always be used to apply the necessary forces required, 2) failure of a pole in testing would probably result in disruption to the network. For these reasons, proof loading has not been considered seriously for routine pole testing work.

2.7 Vibration

The decay of part of a pole will result in changes of the Young's Modulus and density in the region of the decay. These changes have been considered likely to affect the vibrational characteristics of the pole and, if these could be measured, an estimate of pole condition could be obtained. Excitation of the pole is usually either by a single blow from an impact hammer or a repetitive, cyclical force. One of the earliest methods (The Resotest [10]) relied on a square wave force input to the pole approximately 1m from the ground and measurement of the response at intervals going down to ground level. Initially reported tests seemed to be encouraging but little further information could be found (26 years later), so it would appear that the system failed to live up to its early promise.

There are a number of difficulties associated with applying vibrational techniques to poles. The bending natural frequencies start at approximately 2

Hz and occur every 10-20 Hz higher up the frequency range. The precise values vary, depending on diameter, number of wires that are supported, presence of stays, additional masses supported on the pole etc. Internal decay will only affect the bending strength and hence bending frequencies slightly until the point of collapse so the likelihood of detecting any change due to decay is extremely small. Despite these disadvantages, the vibrational approach has been used successfully on railway sleepers [11] where structural parameters between sleepers are much more regulated than for poles. The manufacturers of the sleeper tester have tried applying their method to poles but abandoned their research due to the problems previously identified.

It can be seen that considerable research effort [1-11] has been put in worldwide over the last 30 years in an effort to improve the reliability of wooden poles used in supporting cable networks. Because of the limited success of previous, alternative studies it was decided to look more closely at the standard vibro-acoustic method, which has been relied upon for decades and see if it could be improved by using modern technology.

3. THE IMPACT RESPONSE OF WOODEN POLES

Striking any object or structure with a hammer causes it to vibrate and this vibration may cause the surrounding air to vibrate thus producing the sound of the impact that is heard. It was considered that it was this sound that pole testers use to identify decay in poles. The structure, which is struck, usually vibrates at one or more of its natural frequencies. Usually, only frequencies which are in the range $0 \approx 1500$ Hz can be excited by a hammer blow [12]. Verbal description by pole testers suggested that the characteristic pitch or frequency of the impact sound fell when a decayed pole was struck compared to a "good" pole. This implies that one or more of the natural frequencies reduce due to the presence of decay.

To investigate the vibrational characteristics of a wooden pole a number of finite element models were produced in order to obtain the natural frequencies and determine how these frequencies were affected by the presence of decay. In order to produce the finite element models it was necessary to establish representative material properties for the wooden poles. A number of references were consulted [14,15,16] which highlighted the variability in material parameters and the orthotropic nature of wood as a structural component. Table 1 lists the isotropic properties that were adopted (average values from [14,15 & 16]) as being representative of Scots Pine (the most common wood used for poles in the UK).

3.1 Beam Element F.E. Model and Results.

Based on data for poles, typical dimensions of 180 mm diameter and 6.88m height were assumed. The theoretical natural frequencies in bending for a cantilever can be estimated from [17] and are given by:-

$$\omega_1 = 3.52\sqrt{(EI/mL^3)}$$

$$\text{and } \omega_n = [(2n-1)\pi/2]^2\sqrt{(EI/mL^3)} \quad \text{for } n=2,3,4\ldots\ldots$$

Using wood property values identified in Table 1, the natural frequencies in bending for the pole were calculated and are presented in Table 2.

The first F.E. model was made up of 9 beam elements. The 3 nearest the ground were 0.33 m long, the next 5 were 1 m long and the final element was 0.88 m long, producing an overall pole height of 6.88m. The cross sectional properties of the lowest element were modified to represent the progress of decay from the centre of the pole radially outwards. The 2nd moment of area was reduced assuming no strength was provided by the decayed part of the cross section and the density of the element was reduced assuming that the mass of the decayed section had been removed. The properties were adjusted to represent symmetrical decay extending to 50%, 75%, 85% of the radius of the pole. Natural frequencies and mode shapes were then calculated for each model [18] and the results are shown in Table 2.

3.2 Isotropic Brick Element F.E. Model and Results

To model the 3 dimensional vibration behaviour of the pole it was only possible to model a short section. A length of 660 mm was chosen to enable the radial modes to be represented accurately (excited by a hammer impact of ≈ 25mm diameter). A central section 300 mm long was assumed to be subjected to decay. The short pole was expected to display unrealistic, high bending frequencies but this was not considered to be important and is largely ignored in subsequent analysis.

The material properties as defined in Table 1 were adopted and radial decay representing 50%, 75% and 85% were again modelled and as before the decayed material was assumed to have been removed from the pole. The X-Z plane was assumed to be a plane of symmetry, thereby requiring only one-half of the pole section to be modelled. Figure 1 shows the F. E. model developed.

The results from the model are presented in Figure 2 and plots of the various radial mode shapes are included in Appendix 1 .

3.3 Orthotropic Brick Element FE Model and Results

In general orthotropic 3D stress analysis, the stress- strain relationship is :-

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{Bmatrix} = [C] \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{Bmatrix}$$

where

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{22} & C_{23} & 0 & 0 & 0 \\ & & C_{33} & 0 & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & & & & C_{55} & 0 \\ & \mathit{Sym} & & & & C_{66} \end{bmatrix}$$

And x,y and z refer to the global coordinate system.

The components of [C] are obtained by inverting the following matrix :-

$$[C] = \begin{bmatrix} 1/E_x & -\nu_{yx}/E_y & -\nu_{zx}/E_z & 0 & 0 & 0 \\ & 1/E_y & -\nu_{zy}/E_z & 0 & 0 & 0 \\ & & 1/E_z & 0 & 0 & 0 \\ & & & 1/G_{xy} & 0 & 0 \\ & & & & 1/G_{yz} & 0 \\ & sym & & & & 1/G_{zx} \end{bmatrix}^{-1}$$

where

$$\nu_{xy}E_y = \nu_{yx}E_x \qquad \nu_{xz}E_z = \nu_{zx}E_x \qquad \nu_{yz}E_z = \nu_{zy}E_y$$

and

$$G_{xy} = \frac{E_y}{2(1 + \nu_{xy}E_y/E_x)}$$

$$G_{yz} = \frac{E_z}{2(1 + \nu_{yz}E_z/E_y)}$$

$$G_{zx} = \frac{E_x}{2(1 + \nu_{zx}E_x/E_z)}$$

The material property values used in the orthotropic models are listed in Table 1 and were taken from [16].

The values quoted above were entered into the matrix and MATLAB [19] was used to invert the matrix for input to the F.E. model. The results are included in Figure 3

3.4 Orthotropic Brick Element FE model of Short Pole Section.

A freely suspended short section of pole was modelled using the orthotropic brick elements described in section 3.3. The material properties used were as previously described. Once again symmetry about the X-Z plane was assumed resulting in the half model as shown in Figure 4. The supports were flexible beam elements to ensure there was no interference with radial motion of the pole.

The natural frequencies of the short pole were obtained for the various amounts of decay and the results are summarised in Figure 5.

To investigate the effect of a check in the pole, the short pole model with a 75 mm diameter central hole was used and the freedom constraints were removed gradually from the outer radius through to the inner radius. The results are included in Figure 6.

4. EXPERIMENTAL INVESTIGATION OF POLE SECTION.

A 300 mm section of telegraph pole was obtained from a pole, which had been condemned. There was found to be no sign of decay in the pole when it was sectioned and the section tested appeared to be sound wood. Two “cup” hooks were screwed into the pole near the top surface 180^o apart as shown in Figure 7. The section of pole was suspended in an anechoic chamber and 4 positions marked on the mid-plane at 90^o spacing as shown in Figure 8.

A microphone was positioned approximately 0.5 m away from the suspended pole at the mid-plane level. The pole was tapped with a hammer at each of the 4 positions and the sound analysed using an Ono-Sokki FFT analyser. Figure 9 shows a typical spectrum obtained from the acoustic signal.

A 25mm hole was drilled axially through the centre of the pole to represent decay and the measurements repeated. A 50 mm hole and then a 75mm diameter hole were also tested. Any further enlargement of the hole would have been difficult due to the presence of checks, which would have resulted in the hollowed pole breaking apart. The checks can be clearly seen to penetrate to the inner radius of the pole in Figure 7. Dominant frequencies were identified from the acoustic spectra and are presented in Figure 10.

5. ALGORITHM DEVELOPMENT.

The FE work had shown that there was a correlation between the amount of decay in a pole and the decrease in radial vibrational/acoustic frequencies. Sound recordings of hammer impacts were taken from a large number of poles, which had been in service for varying lengths of time. 50 samples were identified as being from poles in good condition where there was no evidence of decay and 50 from poles where decay was confirmed by drilling. The 100 sounds provided a testsuite upon which various signal processing algorithms could be tested. Figure 11 shows a typical impact sound in the time and frequency domain.

A variety of signal processing techniques were tried and their performances compared. All were configured to produce a rating from 0 to 10 where 0 indicated the presence of severe decay and 10 indicated a sound pole. Two algorithms were found to produce good results. The first was related to the frequency content of the acoustic signal and the second to the rate of decay of the signal. The outputs from each algorithm were combined (to provide an average rating) for each impact sound to improve the reliability of the diagnosis and the results are shown in Figure 12.

6. METER DEVELOPMENT.

Based on the algorithms identified a small number of prototype meters were developed. The general appearance is shown in Figure 13. The sound is captured by a microphone and then digitised for signal processing. The display provides an indication of the score as calculated by the algorithms and the meter is capable of providing further information to aid future algorithm development. Field trials are currently being carried out.

7. DISCUSSION.

There are approximately 4.5 million telegraph poles in the UK and approximately 40 million in the USA. It is thought that electrical utility operators will be responsible for similar numbers of poles. Data for other civilised countries are not freely available but the scale of the problem of maintaining such a global infrastructure can be comprehended. Hence the worldwide research effort to improve diagnostic techniques for identifying the presence of decay in poles. Despite this effort none of the techniques developed [1-11] have found universal appeal over the traditional poletester's approach of striking the pole with a hammer and listening to the noise that is made. Lack of improved accuracy and often significantly increased costs have precluded wide scale adoption of alternative techniques. This has provided the incentive for the present line of research.

To understand the underlying principles behind the existing approach a number of finite element models were produced to represent "good" poles and those with decay present. When wood decays it loses its strength and the Young's Modulus decreases. The density also is reduced. In cases of severe decay, both the strength and mass can be neglected. This assumption (zero E and ρ) was adopted for the present study in the absence of any real understanding of the magnitude of these parameters with intermediate levels of decay.

The first FE model, based on beam elements showed that the bending frequencies were almost immune to the influence of decay until the decay had progressed to 85% of the radial dimension. This corresponds to a reduction in 2^{nd} moment of area of the cross section to 50% of the original. Even then the reduction in bending frequencies is at most 10% and it is likely that variations in pole diameter, number of wires, presence of dead loads etc. will cause a greater variation in the natural frequencies. This is probably why previous attempts at developing a system based on measuring pole vibration have not been successful.

Use of brick elements to model the 3 dimensional vibration behaviour of the pole enables the determination of radial modes of vibration. The number of elements required to model a full pole would have been prohibitive so it was considered appropriate to model the lower section of the pole as shown in Figure 1. Even this simplified model took several hours of processing on a 166MHz PC. The results (Figure 2) confirm the minimal reduction in bending frequencies but clearly show the dramatic change in the radial modes of vibration with decay. However the frequencies produced by the analysis are high and unlikely to be excited by a hammer blow. This highlights the shortcomings of assuming isotropic material properties for wood. The third FE model (Figure 4) takes account of the variation in material properties in the 3 directions based on the best data that could be found in the literature. It was assumed that the properties were constant throughout the model although it was recognised that the properties may vary with height, radial location, local abnormalities, etc. but this variation was considered to be negligible compared to the variation in the orthogonal planes. The results are significantly lower than those predicted by the isotropic model and bring the frequencies closer to the values that were observed from practical measurements that were made. Similar reductions in radial mode frequencies were again observed.

To validate the FE analysis a short section of pole was obtained and modelled (Figure 4). The lowest radial frequency was found to start at 2280 Hz, falling to 1100 Hz with a 75 mm central hole present to represent the decay. The second and third radial modes started at 2350 Hz and 2843 Hz respectively showing similar reductions with decay as the first mode. However these frequencies were still significantly higher than the dominant frequencies obtained from the anechoic chamber tests carried out on the pole section (1^{st} frequency starting at 900 Hz and reducing to 300 Hz with 75 mm decay). It was noticed that the pole section along with most poles had significant checks extending radially inwards from the surface. These discontinuities would reduce the strength of the pole section and it was thought that this would result in reduced radial vibration frequencies. To incorporate this into the FE model the symmetry constraints on the model were gradually removed from one side progressing inwards towards the inner surface. This was considered to be representative of a check with increasing penetration. In reality when this “new” free surface vibrates it will contact the opposing face of the check but the approximation was considered acceptable for small amplitudes of vibration. The results (figure 6) show the first radial mode reducing from 1100 Hz to 197 Hz and second falling from 1200 to 413 Hz in the presence of a check which has penetrated from the outer to the inner surface. These lower values of radial frequency lie close enough to the measured acoustical values of 300 and 537 Hz to give confidence in the hypothesis that the sounds heard when striking a pole are largely due to radial vibration of the impacted cross section.

With a better understanding of the mechanisms involved it was considered possible to develop signal processing algorithms, which could identify these changes in sound when poles were impacted. A large number of poles were identified by experienced pole testers as being in either good condition or having decay present. Tape recordings of the impact sounds were made and used for subsequent algorithm development. The presence of decay was confirmed by drilling the section.

After initial work, a test suite of sounds was made up consisting of 50 “good” recordings and 50 decayed pole sounds. A “perfect” algorithm would diagnose each sound correctly and result in a figure of 100% accuracy. The algorithms were arranged to produce a number on a scale from 0 to 10 for convenience of use and it was anticipated that the good pole sounds would result in a high score whereas the decayed poles would produce a lower score with a clear line of demarcation between the two sets of sounds. Two algorithms produced significantly better results than others and as they were based on different aspects of the signal it was decided to combine them to improve the overall reliability of the score. The results are shown in Figure 12. Apart from a cluster of “good” poles to the bottom left of the graph there is a clear line of demarcation at 4.25 with only 2 poles being incorrectly diagnosed. These two cases are very much borderline and discounting the cluster result in an accuracy of 97.7%. The cluster was found to be from tests carried out at a particular site when conditions were very wet. It would appear that if the wood is wet, the natural frequencies are reduced for sound wood. This is likely to be due to the wood cell walls adsorbing moisture and softening, resulting in a reduction of Young’s Modulus and an increase in density if the moisture content of the cells increases. The moisture content of wood can be readily measured using a handheld resistance meter and to overcome the influence of moisture on the decay parameter it would be possible, with further research, to incorporate a factor in the algorithm to compensate for this. Alternatively it would be possible to advise the tester that testing should not be carried out until the moisture content had fallen below a suitable threshold.

The prototype decay meters are compact and could be produced relatively cheaply (less than half the cost of replacing an incorrectly diagnosed pole) so are considered to be cost effective. The accuracy is considered to be acceptable bearing in mind that the figures are quoted for a single impact. Averaging 3 readings at a section of pole are likely to increase the reliability of the diagnosis beyond 99%. The time required to take a reading is only slightly longer than that required for the existing aural approach so adoption by field personnel should not pose a major problem to introduction of this new technology.

8. CONCLUSIONS

Finite element analyes of wooden poles have been undertaken to obtain natural frequencies of vibration. It has been shown that the radial modes of vibration correlate well with dominant frequencies, which can be heard when the pole is struck with a hammer although orthotropic material properties and modelling of checks are required to achieve quantitative agreement between model and experiment.

Signal analysis techniques have been used to develop 2 algorithms based on the acoustic signal obtained from a hammer-pole impact in order to diagnose decay within a wooden pole section. Neglecting signals from poles which were wet resulted in an accuracy of 97% for the algorithms adopted. A portable meter based on the algorithms is described which is expected to increase the accuracy of decayed pole diagnosis compared to existing techniques.

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Beam and Isotropic Models.

Young's Modulus (sound wood) = 9 GN/m^2

Density (sound wood) = 510 kg/m^3

Poisson's Ratio = 0.25

Orthotropic Models.

E_x = 0.83 GN/m^2 (Radial direction)

E_y = 0.48 GN/m^2 (Circumferential direction)

E_z = 9.6 GN/m^2 (Longitudinal direction)

ν_{xy} = 0.47, ν_{xz} = 0.041, ν_{yz} = 0.033

G_{xy} = 0.07 GN/m^2 , G_{yz} = 0.62 GN/m^2, G_{zx} = 0.69 GN/m^2

Table 1. Material properties for Scots Pine pole models.

	ω_1	ω_2	ω_3	ω_4 (Hz)
Theoretical (No decay)	2.24	14.1	39.3	77.0
Beam F.E. (No decay)	2.24	14.0	39.2	76.9
Beam F.E. (50% decay)	2.22	13.9	39.0	76.7
Beam F.E. (75% decay)	2.15	13.6	38.2	75.4
Beam F.E. (85% decay)	2.04	13.1	37.3	74.0

Table 2 Theoretical and Beam Element F.E. results for bending vibration of a typical pole.

CAPTIONS.

Figure 1 3D brick model of pole with decay to 85% showing restrained freedoms.

Figure 2 Natural frequencies of isotropic FE model showing influence of decay.

Figure 3 Natural frequencies of orthotropic FE model showing influence of decay.

Figure 4 Orthotropic model of short pole showing restrained freedoms.

Figure 5 Natural frequencies of orthotropic FE model of short pole freely suspended.

Figure 6 Natural frequencies of orthotropic FE model of short pole showing effect of check penetration.

Figure 7 Short pole section showing cup hooks and 75 mm central “decay” hole.

Figure 8 Short pole section in anechoic chamber and microphone location.

Figure 9 Time and frequency domain signals obtained from short pole section with 50 mm central hole.

Figure 10 Dominant frequencies of short pole section.

Figure 11 Typical acoustic signal obtained from pole impact.

Figure 12 Combined decay parameter.

Figure 13 The Pole Decay Meter.

Appendix 1 3D Isotropic radial modes of vibration.

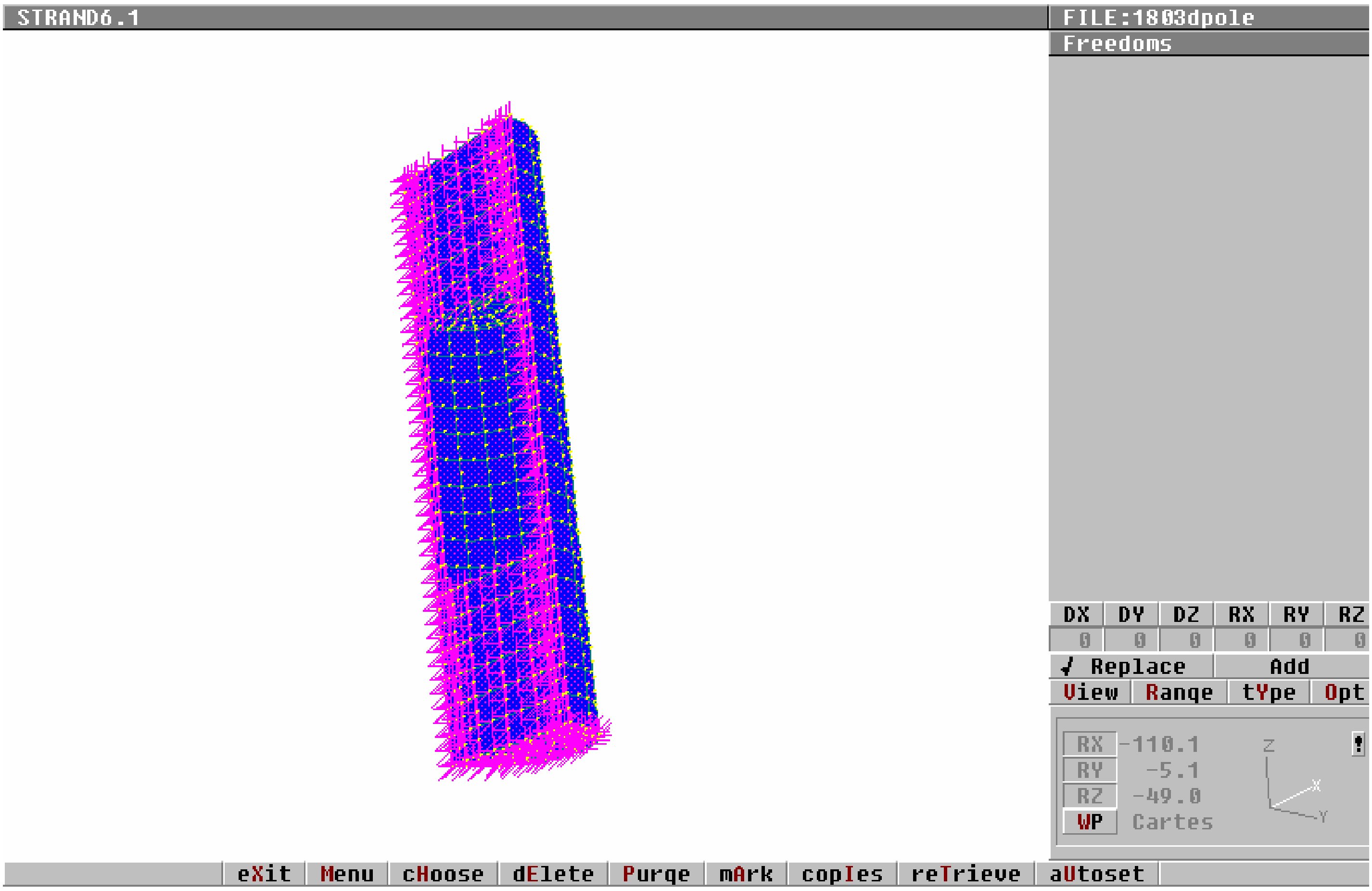


Figure 1 3D brick model of pole with decay to 85% showing restrained freedoms.

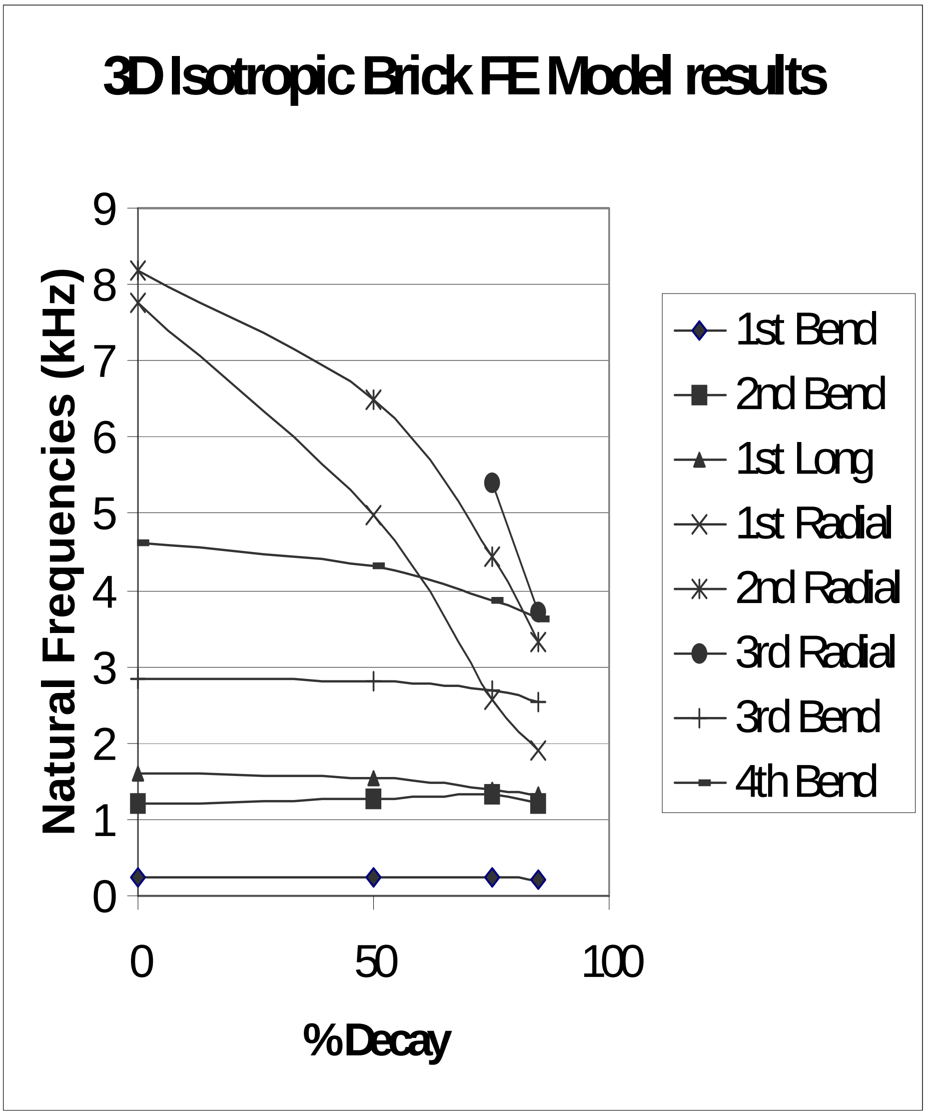


Figure 2 Natural frequencies of Isotropic FE model showing influence of decay.

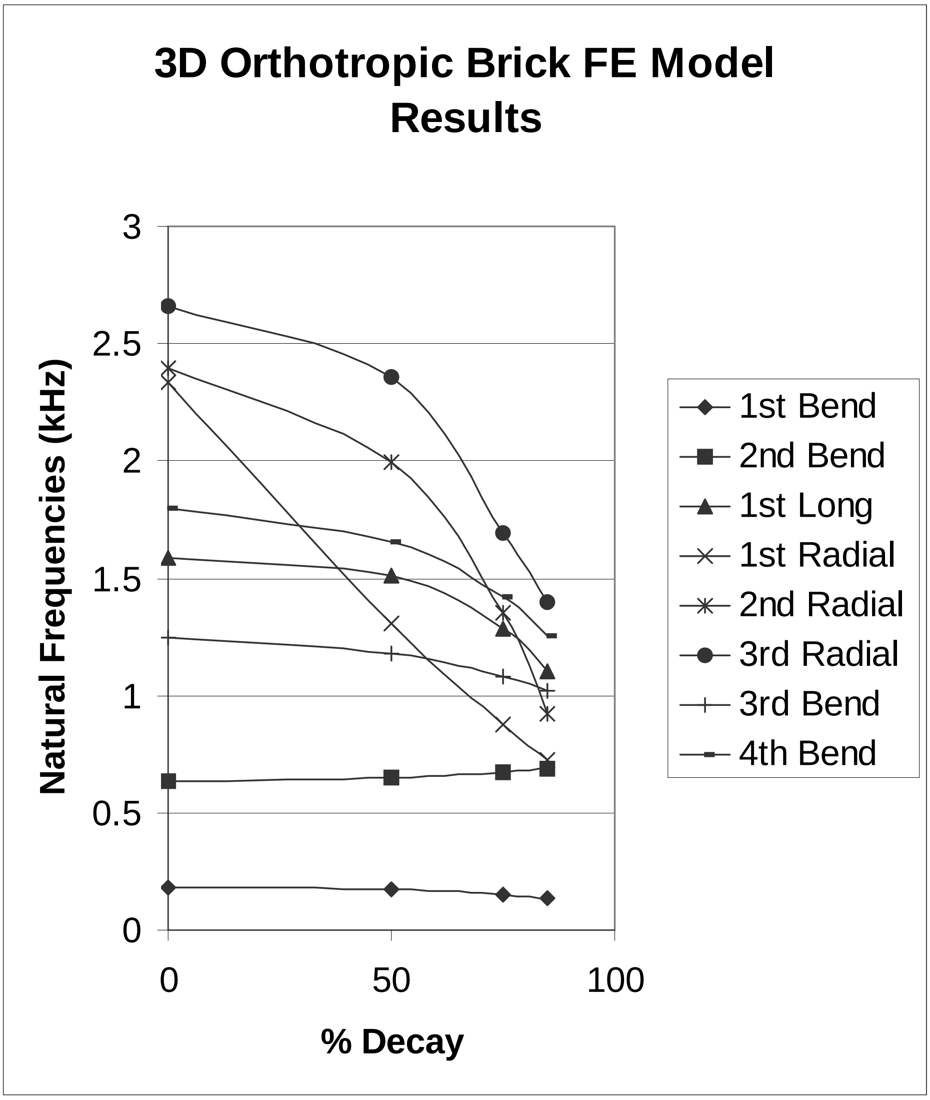


Figure 3 Natural frequencies of orthotropic FE model showing influence of decay.

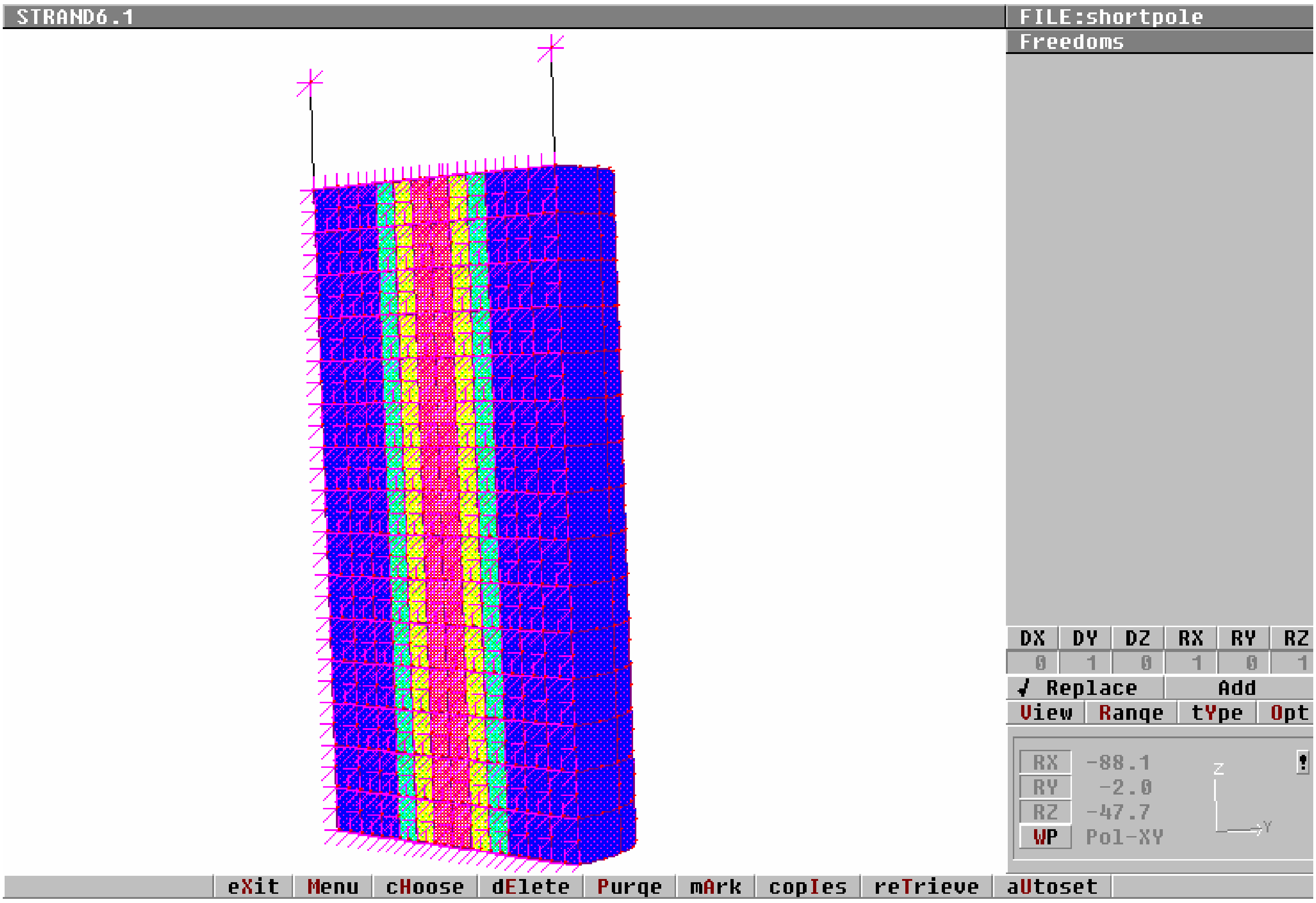


Figure 4 Orthotropic model of short pole showing restrained freedoms

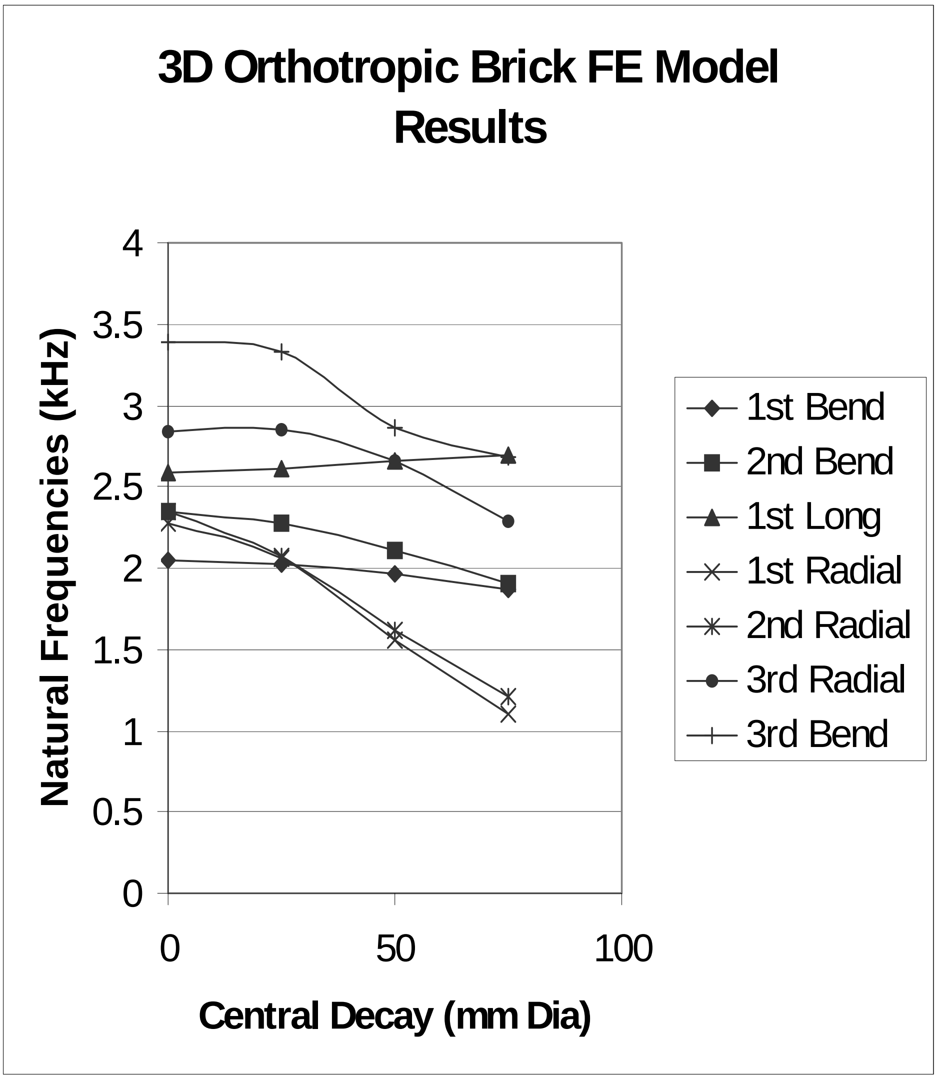


Figure 5 Natural frequencies of orthotropic FE model of short pole freely suspended.

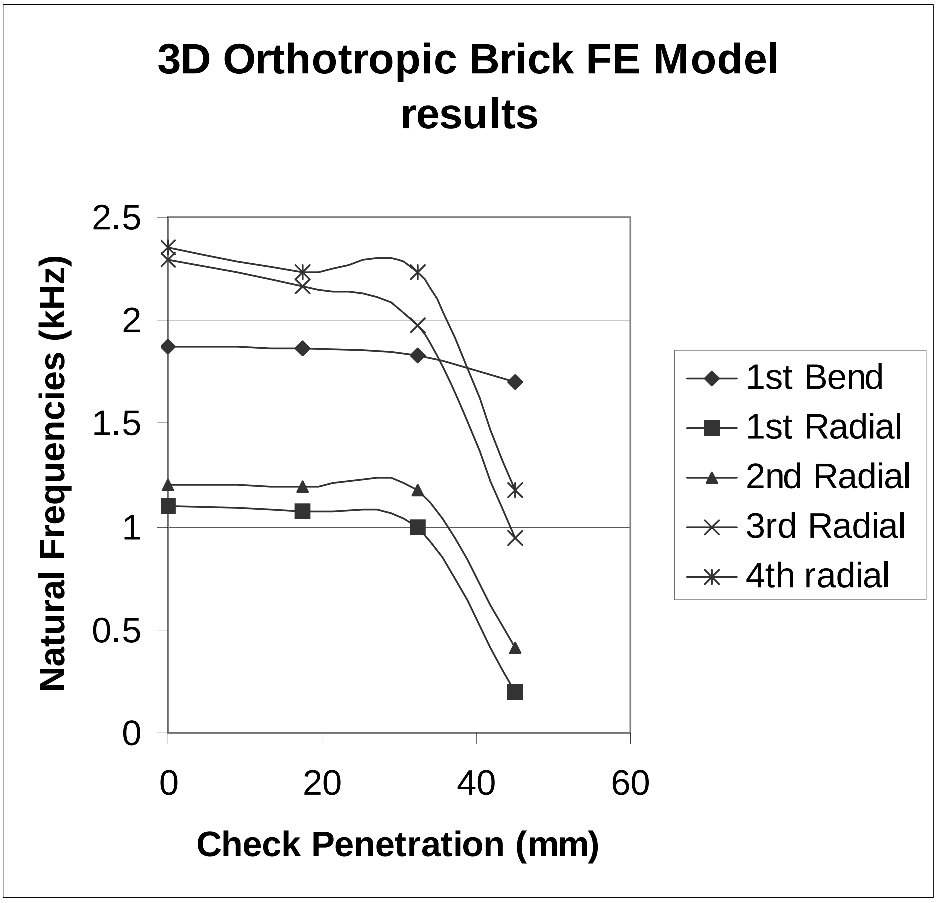


Figure 6 Natural frequencies of orthotropic FE model of short pole showing effect of check penetration.

Figure 7 Short pole section showing cup hooks and 75 mm central “decay” hole.

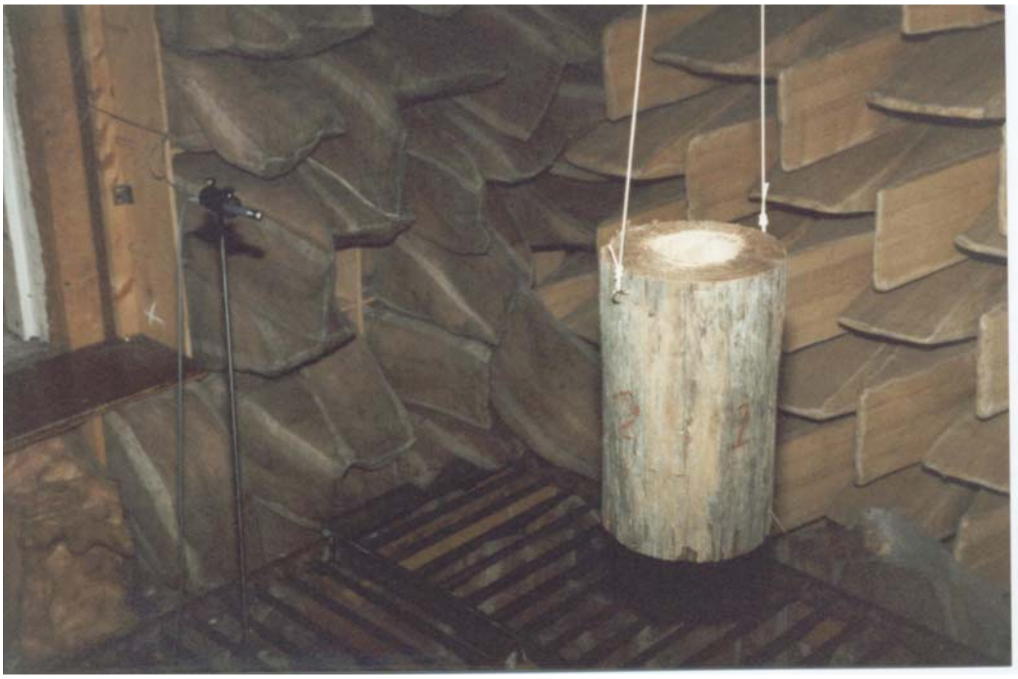


Figure 8 Short pole section in anechoic chamber and microphone location.

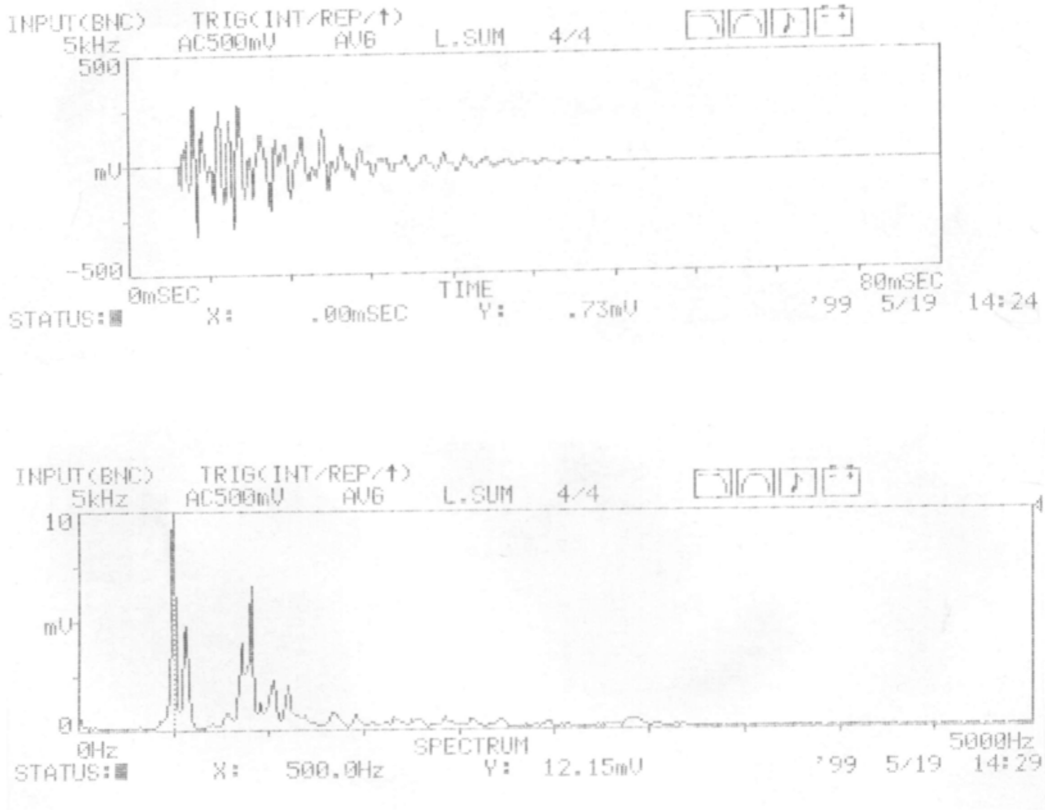


Figure 9 Time and frequency domain signals obtained from short pole section with 50 mm central hole.

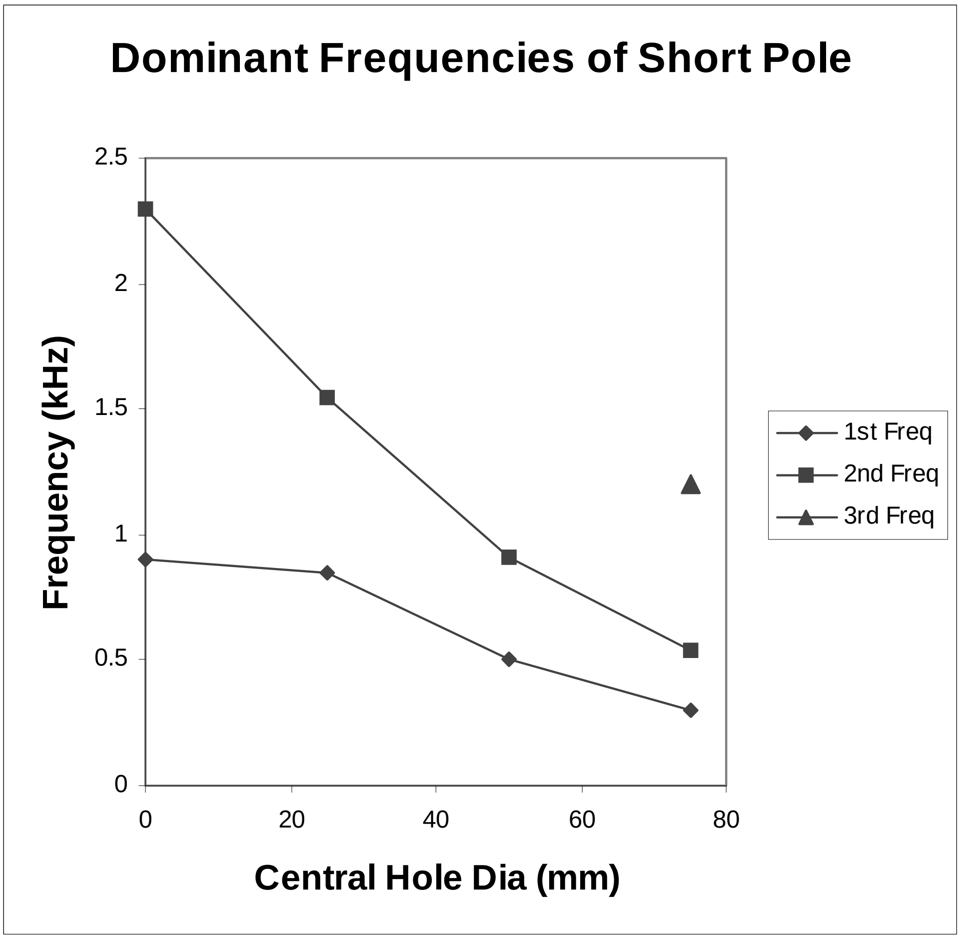
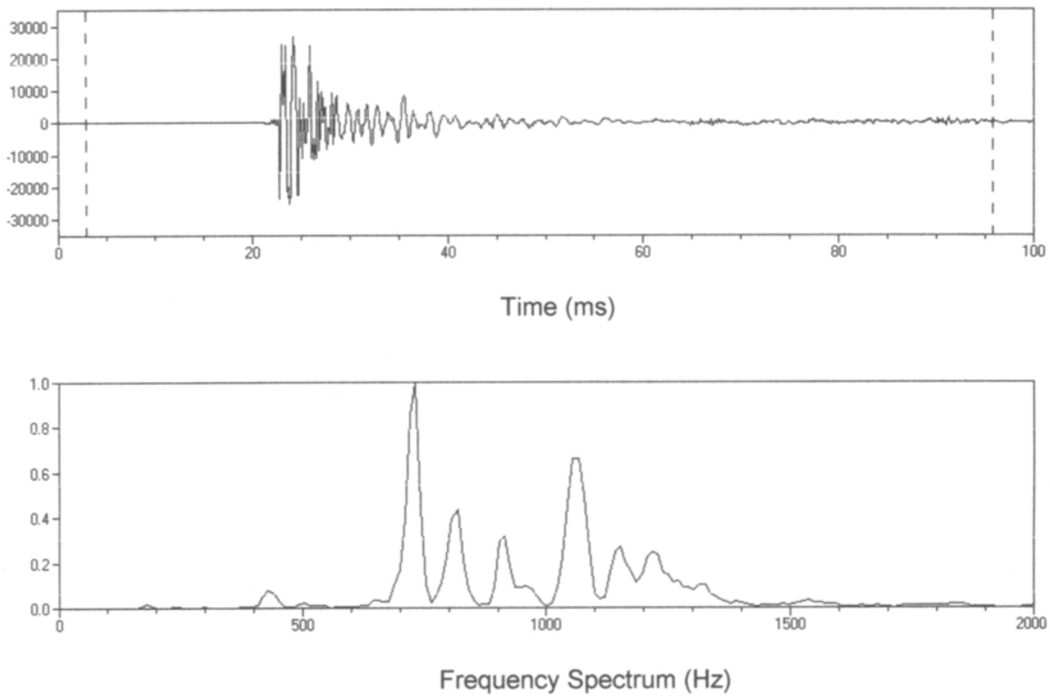


Figure 10 Dominant frequencies of short pole section.



Audio Sampling Rate: 11025 samples per second.

Samples Presented to FFT: 1024 samples from sample 32 to 1055.

Fourier Weighting Window: Cos2.

Frequency Weighting: A-Law.

Fourier Low Frequency Cutoff: Disabled.

Fourier High Frequency Cutoff: Disabled.

Fourier Smoothing: Disabled.

Fourier Vertical Scale: Relative (i.e. values adjusted so highest peak is always at 1.0).

Figure 11 Typical acoustic signal obtained from pole impact.

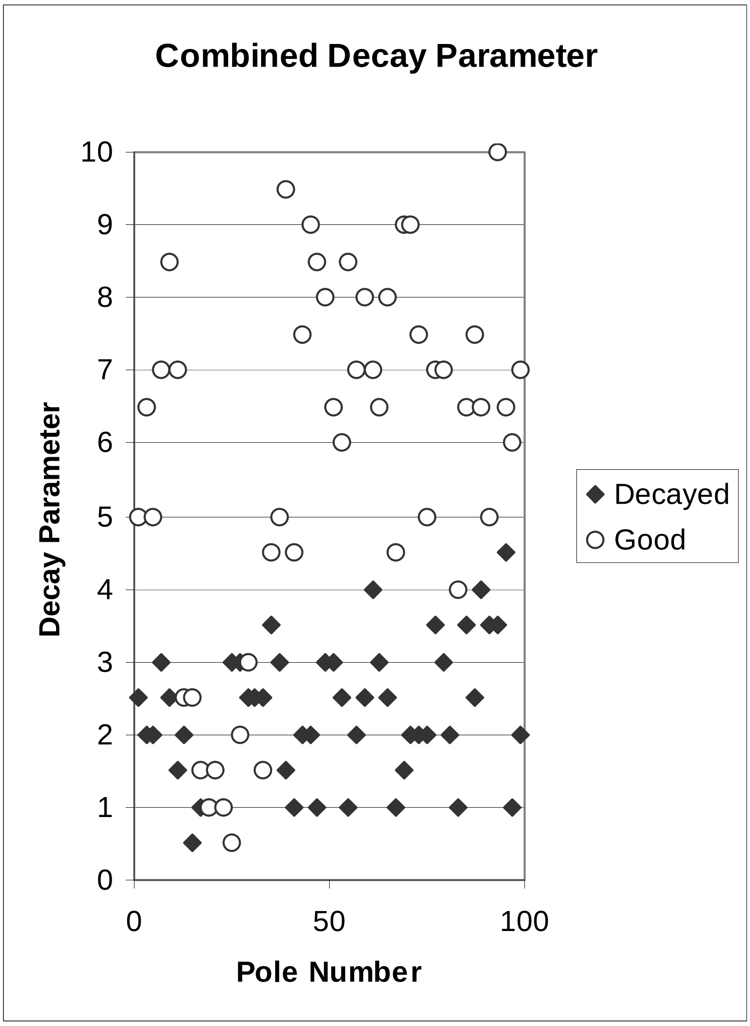


Figure12 Combined decay parameter

Figure 13 The pole decay meter.

Appendix 1 3D Isotropic radial modes of vibration.

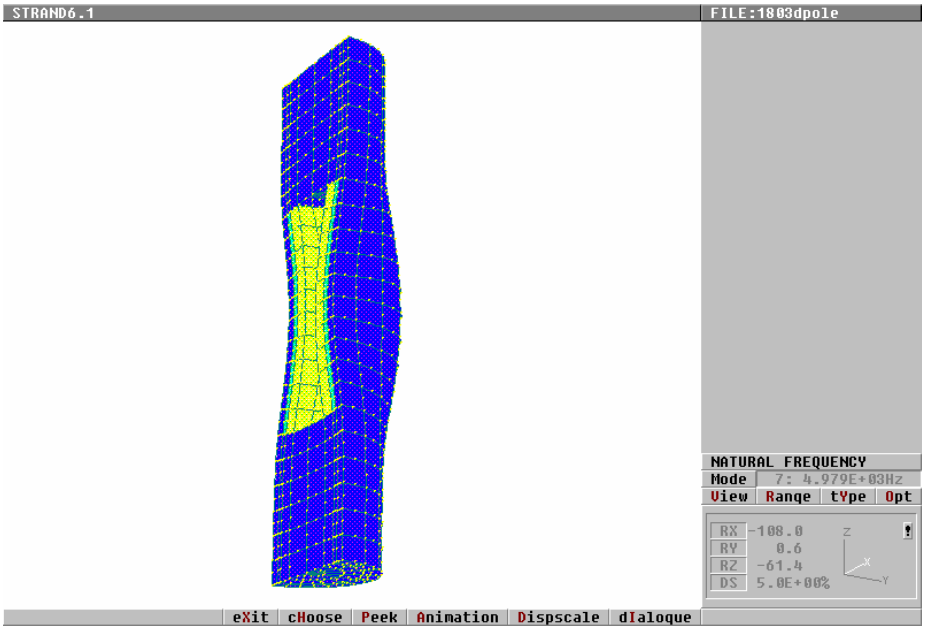


Figure A1 1st radial mode for pole with 50% decay.

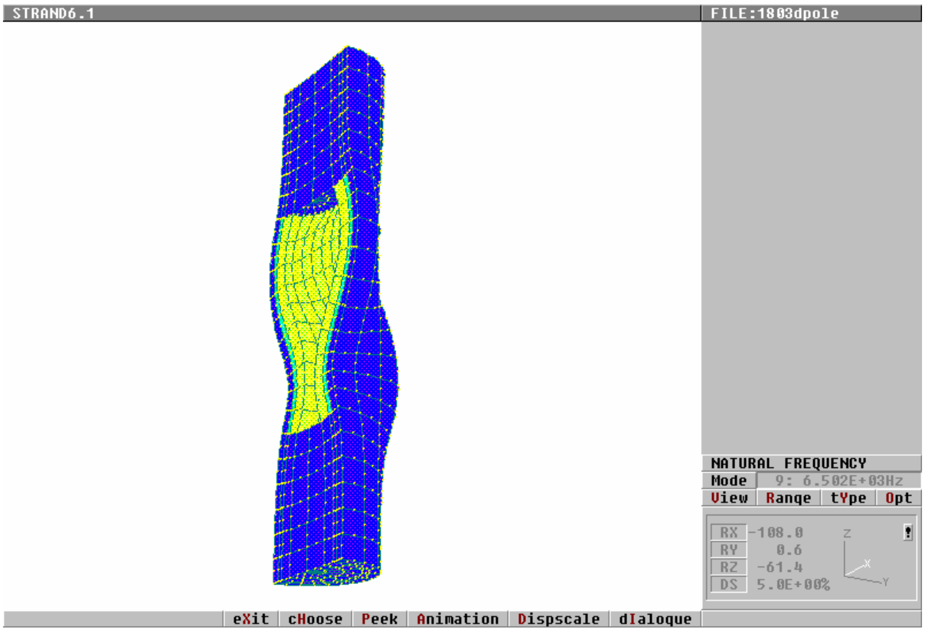


Figure A2 2nd radial mode for pole with 50% decay

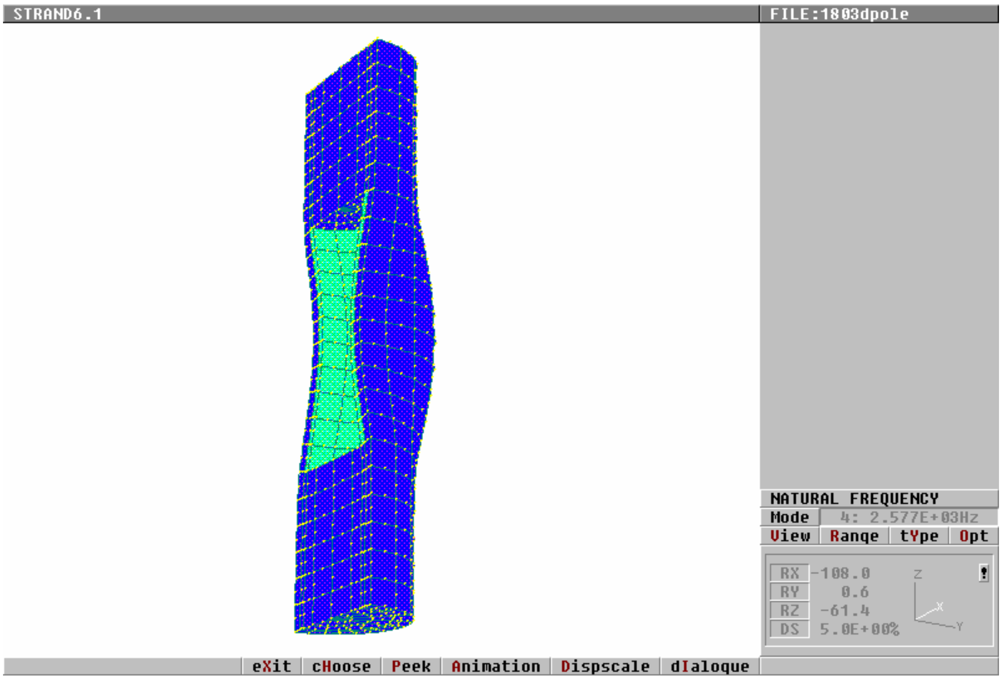


Figure A3 1st radial mode for pole with 75% decay.

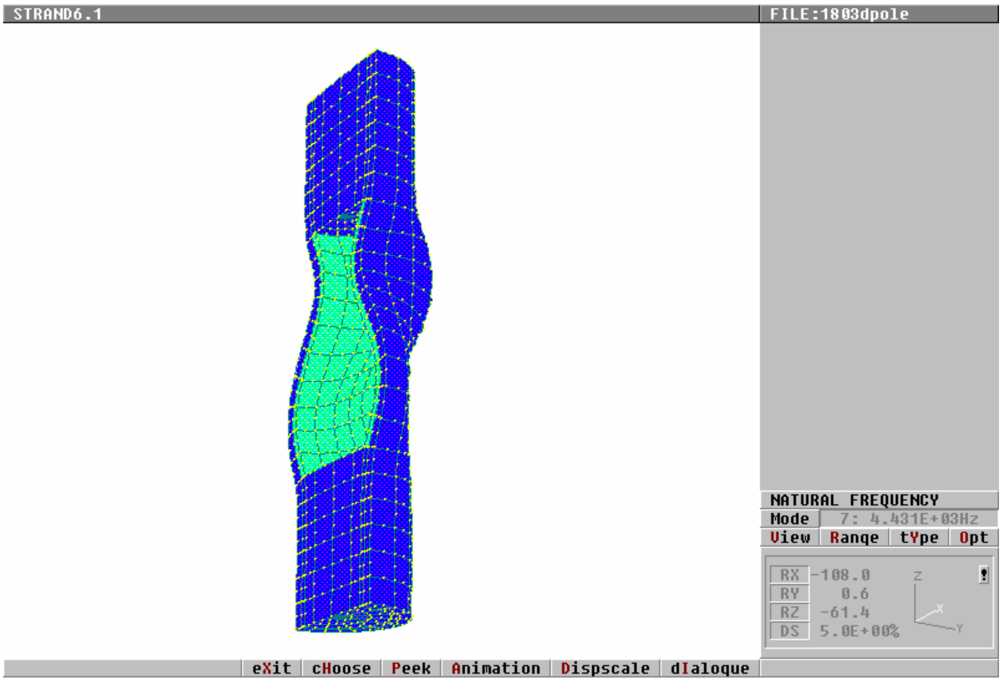


Figure A4 2nd radial mode for pole with 75% decay.

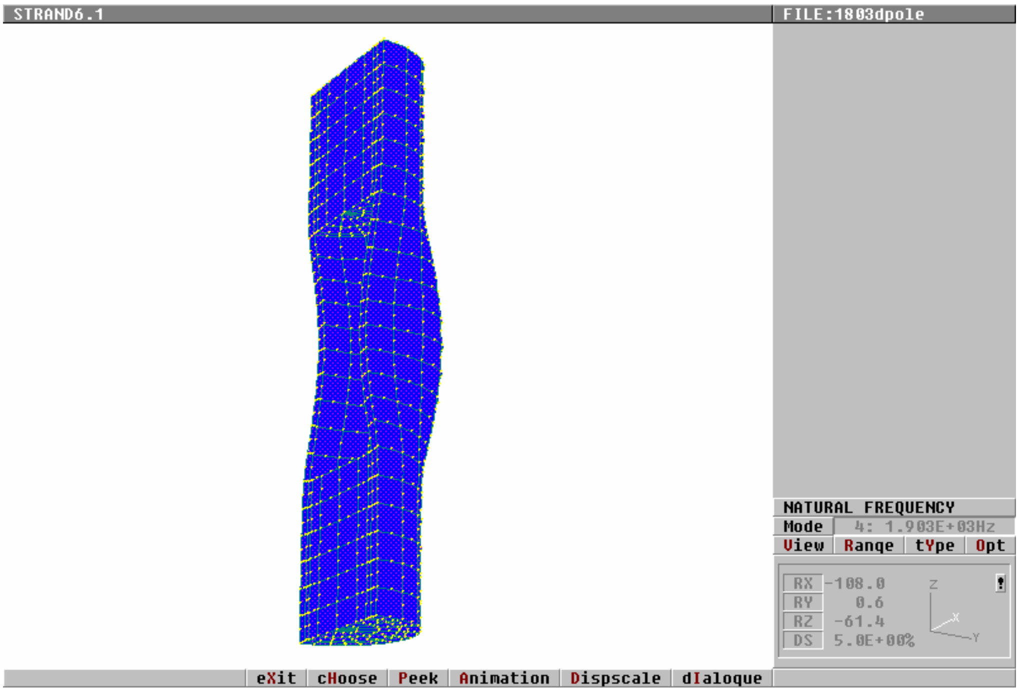


Figure A5 1st radial mode for pole with 85% decay.

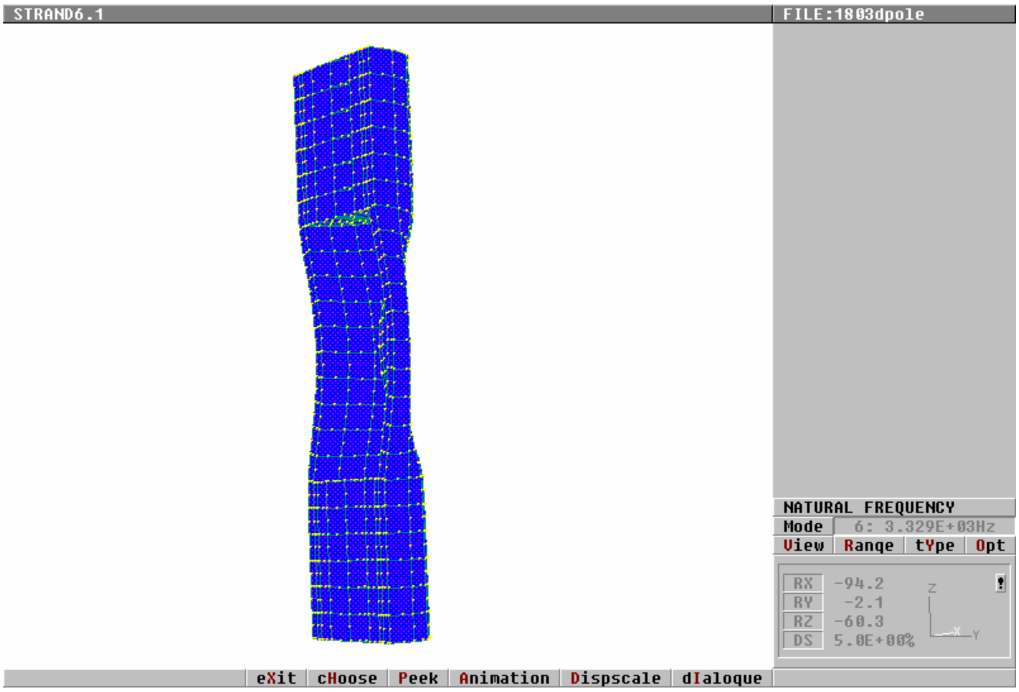


Figure A6 2nd radial mode for pole with 85% decay.