Dynamic testing as a diagnostic technique in orthopedics
by Clark Joseph Mozer

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mehhanical Engineering
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Abstract:
The purpose of this study was to demonstrate the feasibility of using the sound transmission characteristics of bone as a diagnostic tool in orthopedics. This was done by analytically predicting the change in dynamic response of the human forearm due to changes in the bone material properties in various portions of the forearm. It is hypothesized that the response of a portion of the human body to a low-frequency (100 to 1000 Hz) sinusoidal force is an objective indication of the state of health of the skeleton in that portion of the body. Therefore, a change in the dynamic response of that portion of the body would reflect a change in the state of health of the skeleton. This points to the use of the dynamic response test as a diagnostic technique in orthopedics.

Since there has not been established a normal sound transmission characteristic which relates the physical parameters of the body to the dynamic response, it is anticipated that this diagnostic technique is more immediately applicable to detecting changes in the state of health of the skeleton. Such a technique could be useful in tracing the healing of a damaged bone as treatment is administered.

Predictions made by the analytical model indicate that this diagnostic technique may be more sensitive to bony changes in the skeleton than is roentgenography. In addition, measurement of the first natural frequency of a bone may be a more objective indication of the state of health of the bone than is a roentgenograph.

Limitations of the dynamic testing technique are,that bony changes in certain portions of a bone may be difficult to detect. In addition, the ability of this technique to detect a change in sound transmission characteristic is dependent upon the amount of change of the property.

It is anticipated that the research proposed will verify the hypothesis that the use of bone sound transmission characteristics is a useful diagnostic tool in orthopedics and that the dynamic response of. a bone is an objective indication of its health.

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Date August 16, 1974

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IN ORTHOPEDICS

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ABSTRACT

The purpose of this study was to demonstrate the feasibility of using the sound transmission characteristics of bone as a diagnostic tool in orthopedics. This was done by analytically predicting the change in dynamic response of the human forearm due to changes in the bone material properties in various portions of the forearm. It is hypothesized that the response of a portion of the human body to a low-frequency (100 to 1000 Hz) sinusoidal force is an objective indication of the state of health of the skeleton in that portion of the body. Therefore, a change in the dynamic response of that portion of the body would reflect a change in the state of health of the skeleton. This points to the use of the dynamic response test as a diagnostic technique in orthopedics.

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

This thesis has been written in the format outlined by the National Institute of Health for an application for research grant. The research done in preparing this paper was to demonstrate the feasibility of using the sound transmission characteristics of bone as a diagnostic tool in orthopedics. Research is proposed which will further develop this technique as a diagnostic tool and will experimentally verify its effectiveness.

The dynamic response of the human forearm to a low-frequency harmonic force has already been analytically predicted. This study predicted the change in response due to localized changes in bone material properties, as might occur with an osteolytic lesion. These analytical predictions of response changes provide the basis for the research proposal.

OBJECTIVE

The objective of this research is to develop the use of bone sound transmission characteristics as a diagnostic tool in orthopedics. The objective is twofold:

1. Develop experimental techniques and equipment which will provide an objective indication of healing rate as treatment of the disorder is administered.
2. Develop techniques which may aid in early diagnosis of orthopedic disease.

A computer model which predicts the response of a human forearm to a low-frequency harmonic force, together with an experimental apparatus which measures the response of the forearm, have been developed at this university. This computer model has been used to predict the change in sound transmission characteristics of the forearm due to an osteolytic lesion. The results indicate that measuring the sound transmission characteristics of a bone, in this case, the forearm, to a harmonic force may be an objective indicator of the state of health of the bone. This research will confirm or refute these analytically predicted results.

Leukemia is an example of a malignant disease which may affect changes in the skeleton. Recent developments in chemotherapy have made it possible in many cases to rapidly place patients in remission. While in remission skeletal abnormalities as well as other symptoms of the disease disappear. In the case of these patients, the sound transmission characteristics of the bones may be an objective diagnostic indicator of the restoration of the bone matrix to normal.

Although leukemia is presented here as an example of a disease where bone sound transmission characteristics would be useful in diagnosis, obviously there are other orthopedic disorders to which this technique could be applied as an objective diagnostic tool.

BACKGROUND

As a part of this background review, a bibliography of medical literature reviewed is presented in Appendix I.

The need for an early diagnosis in malignant disease is well established. Due to the recent advances in chemotheraphy in the treatment of leukemia, there is an even greater urgency to reach an early diagnosis of hematologic malignancy (1). In an article published in late 1972, Van Slyk (1) states that from a study of 159 children who have survived more than 5 years after diagnosis, it is estimated that over 50 per cent will have normal life spans.

Leukemia is an example of a malignant disease which may present with bone pain and associated osteolytic lesions. B. A. Chaubner (2) points out that in the case of patients with chronic granulocytic leukemia, bone pain suggests an underlying osteolytic process. This process can take place without radiologic changes or hematologic evidence of blastic transformation. In other words, certain bone lesions may not appear on a radiograph, particularly at an early state of the disease. However, it is precisely at this early stage of development in a malignant disorder that the diagnosis is critical. Also critical is having an objective means of evaluating the effects of therapy.

The percentage of the patients who have leukemia who experience bone changes varies. Silverman (3) found bone changes in 70 per cent of the children in his study. Thomas (4) found lesions in 90 per cent of the children he studied and in 57 per cent of the adults. In a more recent survey, Aur (5) found bone changes in 21 per cent of the children. Aur used more strict criteria in determining whether the bone was affected by leukemia, which accounts for the substantially lower percentage in his findings.

The specific lesions which occur in leukemia are varied, depending primarily on the age of the patient and on the state of advance of the disease. They are, briefly, generalized rarefaction of the skeleton, radiolucent transverse bands occurring in the metaphysis of long bones (occurring primarily in children), osteolytic lesions, and cortical and periosteal lesions (4). Thomas (4) found that the osteolytic lesions were very common in both children and adults with leukemia. That the lesions may cause severe bone destruction is illustrated by the cases of vertebral compression reported (6, 7).

The bony changes that occur in leukemia may disappear during remission (1). Bone pain associated with these changes also disappears during remission (4, 1). It is interesting to note, however, that during remission bone pain may disappear and the function restored without improvement in the radiographs (6). This suggests that remission of the leukemic process is not necessarily related to radiologic evidence. It has also been established (5) that bone pain is not necessarily related to roentgenographic findings. These facts suggest the need for a more objective measure of bone property changes than the roentgenographs provide in order to monitor the leukemic process in the bone.

A substantial amount of work has been done in recent years on in-vivo non-destructive testing of bones. Techniques for measuring the response of bone to a low-frequency harmonic excitation have been developed by Jurist (8) and at this university (10, 11, 12). Jurist (9) has applied his measurements of tibial resonant frequency as a diagnostic technique in measuring the strength of fracture unions. He found that this technique shows promise as an accurate indicator of fracture healing.

At this university, Matz (10) made a parametric study of the effects of different physical parameters on the low-frequency vibration response of the forearm. The four physical parameters Matz measured were ulna length, fleshiness, bone size and muscle development. All of these parameters were found to affect the sound transmission characteristics of the forearm. Matz's work is particularly important, because his work can help explain variations from an average response for a large population. There has not been established a "normal sound transmission characteristic" which relates the physical parameters of the subject's forearm to the dynamic response.

E. R. Garner (11) used Matz's experimental apparatus to obtain the response of the forearm of a 34 year old male. He then mathematically modeled the forearm, using the finite element technique, in terms of eight macroscopic biological properties of the flesh and bone in the arm. By adjusting these properties until the analytical response from his model matched the experimental response from Matz's apparatus, Garner determined the macroscopic biological properties of the flesh and bone of the forearm of the subject. Garner's modeling technique enables the investigator to predict changes in the response of the forearm due to changes in the physical properties of the arm.

At this university Harrigan (12) developed improved instrumentation and procedures for determining the response of the forearm to a low-frequency harmonic excitation. He determined four configurations of the apparatus which will provide reliable test data. The four configurations which Harrigan found have frequency deviations of less than 8 per cent. Three of these configurations had frequency deviations from the first bending natural frequency of less than 5 per cent. Thus, Harrigan greatly improved the accuracy with which the first natural frequency of the forearm can be measured.

RATIONALE

Presently, detection of orthopedic disorders is done largely by X-ray. In a large number of cases this is the only diagnostic tool necessary. However, Snider (15) has estimated that a 30 per cent reduction in roentgenographic bone density is necessary to detect any change in the resulting X-ray negative. Thus, with the present diagnostic means, there is room for a great deal of bone damage before the disorder can be readily detected roentgenographically. It seems that there exists a need for a more sensitive diagnostic tool for measuring the integrity of bone.

The bone lesions which occur in leukemia reduce the density and therefore the bending stiffness of the bone matrix. It would be desirable to be able to accurately detect these changes in the structural properties of the bone. One way of doing this is by exciting the bone with a sinusoidal force (a vibration) and then detecting the response of the bone to the input force. The response of the bone will indicate the structural properties (sound transmission characteristics) of the system.

For a continuous system, such as the human forearm, there are an infinite number of natural frequencies of vibration and associated mode shapes (13). Generally the first natural frequency of a system is readily detectable experimentally. Briefly, this is the lowest frequency of excitation at which the amplitude of the response of the system has a maximum. At higher natural frequencies the damping which is present in every real system, and which is very predominant in biological systems, attenuates the displacement of the system to the point where the response is unnoticeable. It is therefore expected that in the measurement of the dynamic response (sound transmission characteristics) of bone, the first and possibly, the second natural frequencies will be observed. These natural frequencies and natural modes are functions of the structural properties (bending stiffness) and inertial properties of the system. Therefore, the dynamic response (sound transmission characteristics) of a system with a given geometry and mass distribution will determine the structural properties of the system. It is precisely these structural properties which indicate the health of the skeleton, which is essentially a structural frame. In the case of leukemia, the state of health of the skeleton may be related to the state of advance of the malignancy.

In the case of a simple beam an analytical prediction of the response of the system presents no problem. However, an analytical prediction of the response of a complicated biological system is a formidable problem indeed. E. R. Garner has used a numerical approximation technique, the finite element method, to approximate the response of the forearm of a 34 year old male to a sinusoidal input force. Garner's work is presented in full in Reference (11).

Garner found that a reduction in both the hydrostatic and deviatoric stiffness of bone would result in a lower first natural frequency for his modeled system. As he points out, this is to be expected since generally a reduction in the stiffness of a structural system will lower the natural frequency of the structure. Garner found that the response was much more sensitive to changes in deviatoric stiffness than to changes in hydrostatic stiffness. Thus, Garner's model predicts that in the case of generalized rarefaction of bone, which would presumably reduce the stiffness of the bone, the first natural frequency of the bone would be reduced. Note that a generalized rarefaction of bone is one of the effects that leukemia has on both adult and juvenile patients.

To examine the predictions of the modeling technique further, the total (hydrostatic and deviatoric) stiffness of a section of bone three inches long approximately midway between the wrist and the elbow of both the radius and the ulna was reduced from zero to fifty per cent of the normal stiffness as determined by Garner. The first natural frequency of this analytically modeled forearm was then predicted. A summary of this procedure is presented in Appendix II. It was found that the peak amplitude of the response reduced linearly with the reduction in bone stiffness (Figure 1). Figure 2 shows the expected change in response of the arm due to a 50 per cent reduction in stiffness in this localized area. Note that the amplitude of the response has reduced slightly and the first natural frequency has moved from 480 Hz to 400 Hz. The bandwidth, B, measured at 75 per cent of the peak amplitude of each curve was increased slightly from 220 Hz to 235 Hz. It is therefore expected that on the basis of these analytical

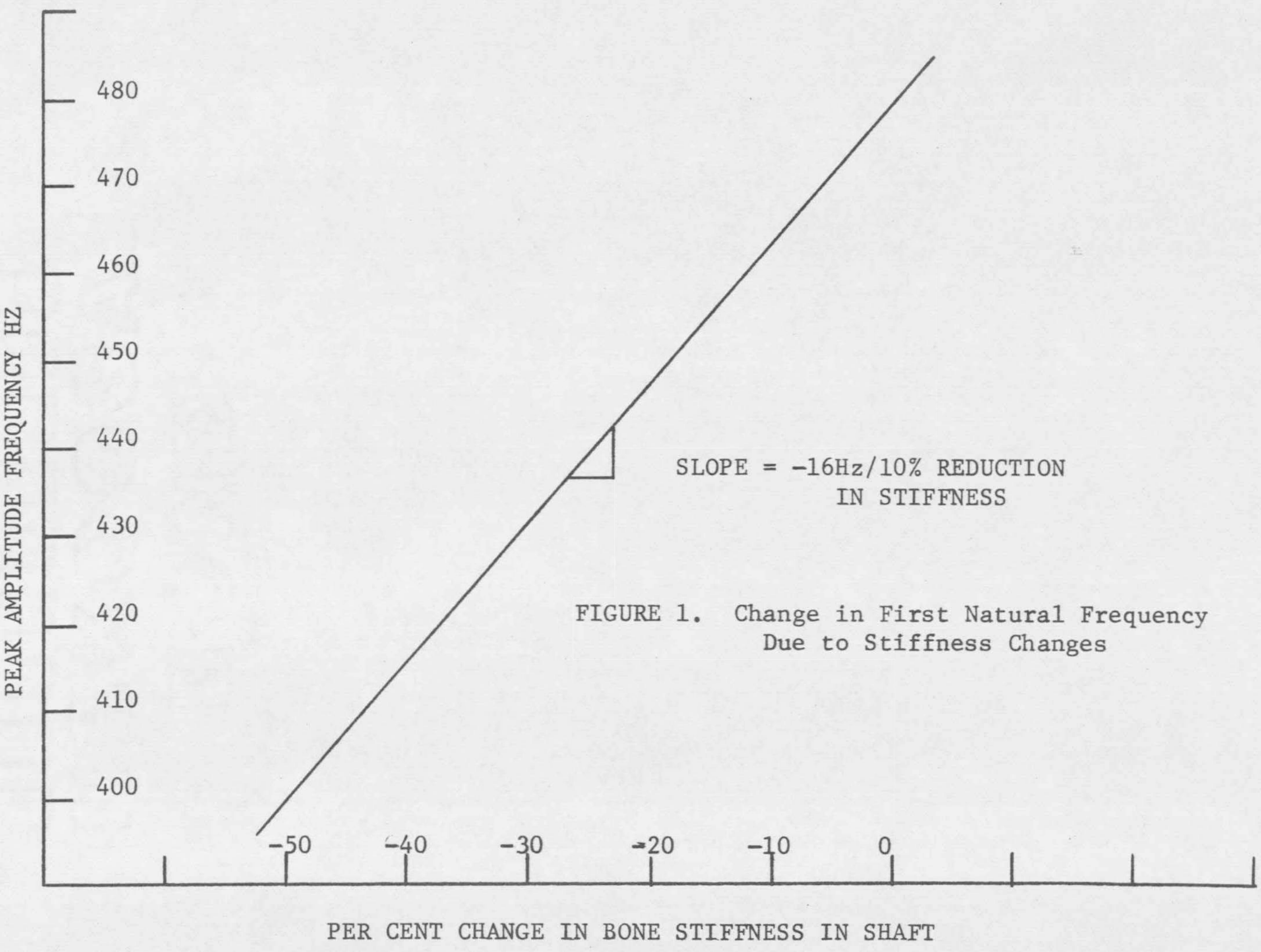

FIGURE 1. Change in First Natural Frequency Due to Stiffness Changes

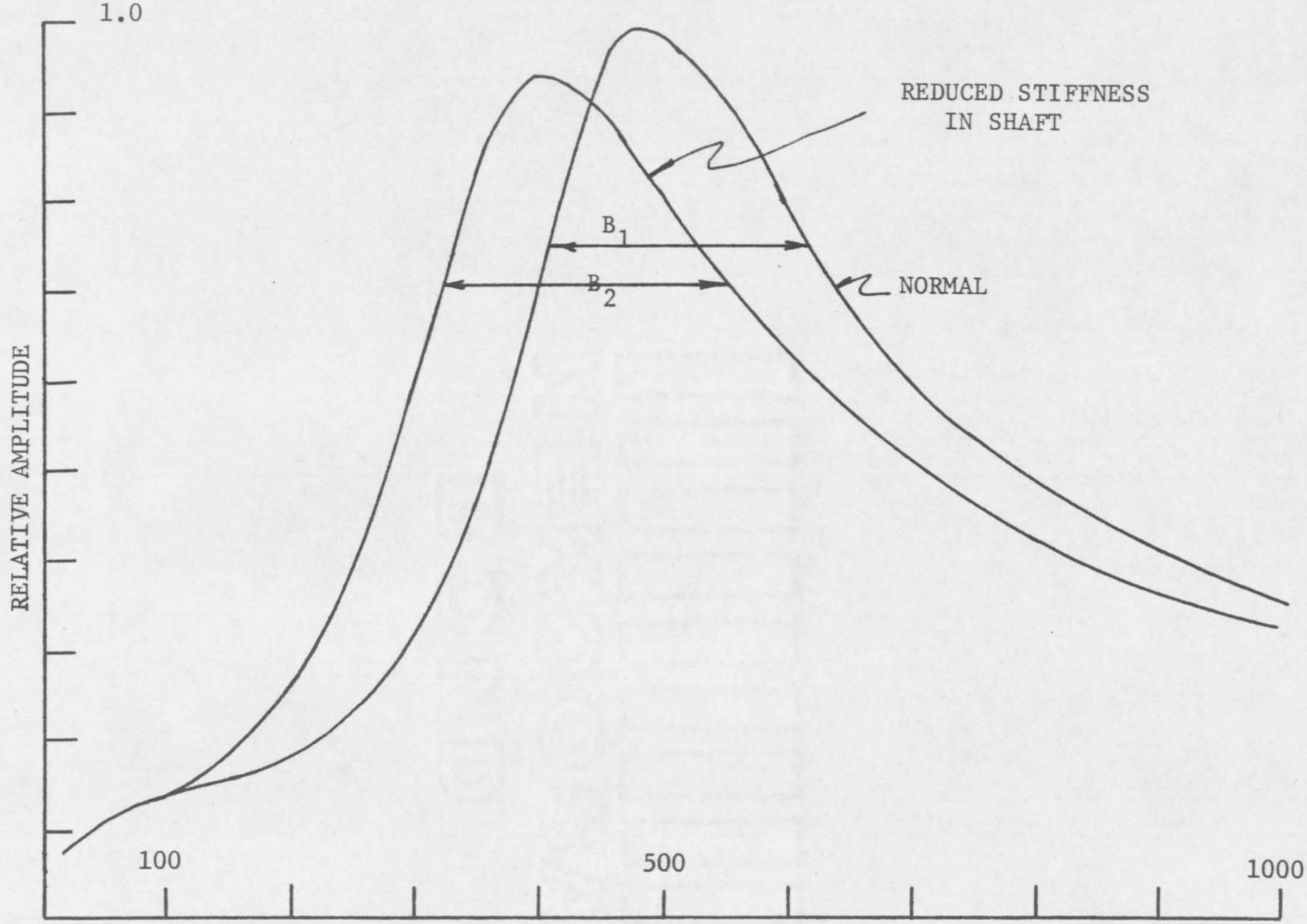

FIGURE 2. The Expected Change in Response Due to a 50 Per Cent Reduction in Stiffness in the Shaft

results, a similar shift in the response curve would occur for a patient with a similar lesion.

To further anticipate the results of lesions in different locations in the arm, the total stiffness of a 1-1/2 inch long section of the forearm located in the wrist was reduced from zero to 50 per cent below the normal value. In this case, however, there was a negligible shift in the frequency response curve. This was not particularly discouraging, since in the case of the first natural bending mode of a system such as this, this is the expected result. In this system the mid-section of the beam is bent more than the end-sections, therefore a change in the structural properties in the mid-section of the beam would affect the response more than a similar change in the end sections of the beam. One of the limitations of the dynamic testing method as a diagnostic technique is that the location of the lesion may be crictical to the detection.

The effect of changes in density in the forearm was also investigated. It was found that a decrease in density either generally or locally increased the amplitude of the response slightly and the resultant first natural frequency was greater than that of the normal system. Figure 3 shows the shift in response due to a 50 per cent decrease in density of a 3 inch long section of the forearm at midshaft. The first natural frequency changed from 480 Hz to 560 Hz and the bandwidth of the first natural frequency increased from 220 Hz to 295 Hz.