NASA Technical Memorandum 4001

An Application of Retroduction to Analyzing and Testing the Backing Off of Nuts and Bolts During Dynamic Loading

James J. Kerley
Goddard Space Flight Center
Greenbelt, Maryland

NASA
National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1987

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PREFACE

The retroductive method of application described in this report is that of the author and does not express the established methods of the Goddard Space Flight Center. This is a new method which only time can verify. The need for new theories is evident as there is no accepted method today for analyzing the backing off of bolts and nuts during vibration. It is hoped that this report will make a contribution to the solution of this most difficult problem.

ACKNOWLEDGMENTS

Through the years scientists such as Boyle, Charles, Newton and others have added specific scientific formulae for engineers to use. Dr. A. Croce has contributed another scientific dimension by showing more than a specific equation. She has developed a mental process which will lead to many other equations and formulae. This method is presented for the first time in this reference publication.

All vibration testing was performed at the Goddard Space Flight Center. The accurate laboratory work that contributed to the tabulated results could not have been done without the experience and skill of George Griffin, Goddard Space Flight Center.

FOREWORD

A detailed understanding of the mechanisms of vibration loosening of bolted joints has long eluded the technical community. Although there are strongly held partial theories, a consensus surely does not exist. In recognition of this situation, a Joint ANSI/ASME Subcommittee on Loosening Mechanisms of Bolted Joints Under Vibration was formed. James J. Kerley of the Goddard Space Flight Center has participated in the subcommittee's activities since the summer of 1982. Mr. Kerley is to be commended for his efforts to reduce this complex problem to some basic principles and to develop a generalized bolted-joint test procedure. The work to date shows strong evidence of Mr. Kerley's background as a dynamicist and a careful experimentalist. His experimental results as published in this report add significantly to the knowledge base from which further work that the subcommittee hopes to promote can benefit.

Portions of this report are devoted to a discussion of "retroduction," an attempt to rationalize the process of engineering discovery. Although the theory is not fully developed, Mr. Kerley and Dr. Croce are to be encouraged with this ambitious objective.

Peter P. Zemanick, Chairman
Joint ANSI/ASME Subcommittee on
Loosening Mechanisms of Bolted
Joints Under Vibration

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NEW STRUCTURED METHOD FOR ANALYZING AND TESTING THE BACKING OFF OF NUTS AND BOLTS DURING DYNAMIC LOADING

James J. Kerley
Goddard Space Flight Center
Greenbelt, Maryland

INTRODUCTION

Work at the GSFC in support of the ANSI/ASME Subcommittee on Loosening Mechanisms of Bolted Joints Under Vibration was initially geared to developing engineering data for selected bolted joints. It was evident from the onset that a universe of joint parameters, applications, and testing possibilities was extant, and a structured means was needed to organize an attack on the problem. The work of Dr. A. Croce on retroduction and dialectics seemed to offer such a means. The bolt loosening problem was used as an example of applying retroduction methods. The various steps and procedures used are presented here as the problem is organized and testing results are analyzed. It is the author's view that the retroduction method leads a practitioner to an effective attack on a given problem and aids in broad communication. It is hoped that understanding and use of the retroduction method will prove fruitful to others.

STUDY METHOD

There is no acceptable mathematical analysis for the backing off of nuts during vibration, nor is there a good understanding of the kinds of dynamic loads that cause this process. The method of study presented here, adapted from the doctoral dissertation of Dr. A. Croce, describes the types of dynamic loads that cause nuts to back off, measures the loads on these bolts and nuts during vibration, and determines the stress distribution in the threads.

To illustrate this method (called "retroduction"), let us apply it to the engineering design problems of a beam. We will describe the method and define the terms as we solve the problem.

Typically, to solve a beam design problem we would take the load, compute the bending moment on the beam, and use a handbook to find a beam that will take that bending moment. Our selection depends on our analysis. Or, we may have a beam similar to one studied previously, and we may subject this beam to a simple test to see if it will do the job. If it is not strong enough, we may choose and test a larger beam, or perform a mathematical analysis to determine the proper size from a previous test. Even after the test, we must perform a mathematical analysis to ensure that the beam will meet all requirements, such as deflections and stresses.

Figure 1 illustrates both of these methods. If deflection is a criterion as in Figure 1, the deflection is calculated as shown. If we are not sure of our calculations, we can buy a beam and test it to check our calculations. Or, if the mathematical analysis is too high, the mathematical analysis will have to conform to the tests. Stress concentration factors and other variables could cause this discrepancy.

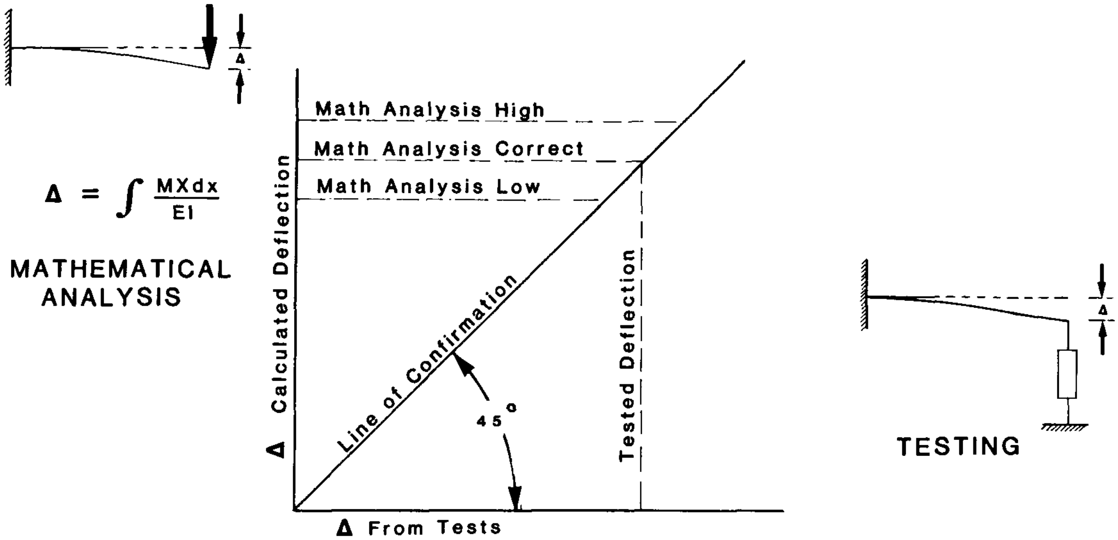


Figure 1. Handbook design.

But what if we do not have a catalog to pick the desired beam or if we have no idea where to begin? We need a new approach to the problem. The question usually asked is: "How was the beam selected in the first place?" If the loads are the same as past loads, the moments the same as past designs, and the deflections about the same as past requirements, we can pick a beam from the handbook from experience.

In many modern designs, however, the circumstances are new; thus, we must choose a beam for which we have no past experience. The only written requirement is that the beam meet a certain deflection. The stress condition is secondary, but we must check it analytically. Retroduction is a dialectic method for finding the right beam in the first place. Dialectic is a logical or rational method of analysis; it is the art or practice of examining opinions or ideas logically, often through questions and answers. Dialectics as the logic of questioning organizes the line of inquiry so that conclusions are reached or put in a form that can be either tested by observation and experimentation or verified by mathematical analysis. (This document discusses two types of analyses: mathematical analysis and logical analysis, in which opinions are discussed to arrive at a starting point for selecting the proper beam—some engineers call this their "ball-park" design.)

The questions of dialectics are prefaced by a number of items both given and known. *Given* by this design problem are the following:

1. The length of the span is given.
2. The loading on the beam is given.

3. The limit of deflection is given.
4. A tight time schedule is given.
5. The beam is in a house in a remote area.

Known from past experience are the following:

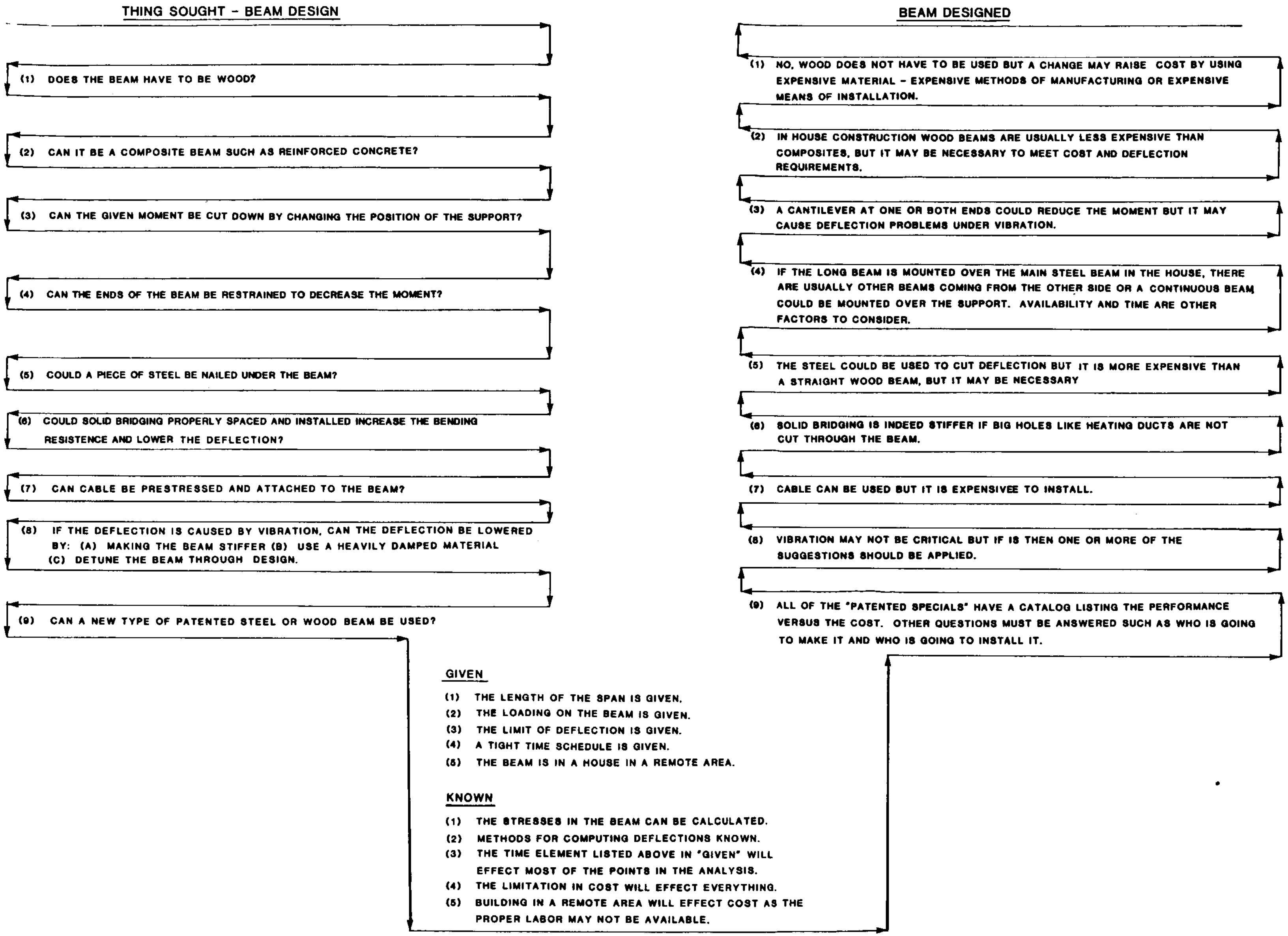
1. The stresses in the beam can be calculated.
2. Methods for computing deflections are known.
3. The time element listed under *Given* will affect most of the points on the analysis.
4. The limitations in cost will affect everything.
5. Building in a remote area will affect cost because the proper labor may not be available.

The next step is to study Figure 2, Retroductive Design: the *Given* and *Known* items appear at the bottom, and the dialectic questions appear on the left. These questions on beams must consider the given and known items at the bottom because these items are known before we start the design and they give direction to the dialectic questions.

Next, we answer each question as it is listed on the right side of Figure 2. In some cases, answers to these questions can be found in handbooks. Let us follow some of the questions to conclusion.

At the top left of Figure 2 is the thing sought, "Beam Design." Drop down to the first question, "Does the beam have to be wood?" Go over to the right, and under item 1, read the *general* answer, "No, wood does not have to be used, but a change may raise the cost by using expensive materials, expensive methods of manufacturing, or expensive means of installation." Follow this procedure through Question 9.

The answers to the questions are always answered with *Given* and *Known* in mind, and they always follow certain principles. (A principle is that from which anything follows. An example is the principle that no material should be used in house construction that could be toxic to the future owners. Each piece of material that goes into the house must follow that principle. A principle may or may not be a rule. But, when you use principles you will come to a logical and clear answer.) In answering the questions on the left, remember the following principles. These are the four causes that *always* lead in the solution of this, or any other, research or design problem. The first principle to consider is final cause, which is always the first thing sought (you want a beam) and the last thing found (the actual beam). In this case, the final cause is a beam to fit into the house construction with *Given* items in mind. The second principle to consider is the material cause: What is it made of? Remember that the first question was: "Does the beam have to be wood?" However, you could not answer this question without knowing the final cause.



THING SOUGHT - BEAM DESIGN

(1) DOES THE BEAM HAVE TO BE WOOD?

(2) CAN IT BE A COMPOSITE BEAM SUCH AS REINFORCED CONCRETE?

(3) CAN THE GIVEN MOMENT BE CUT DOWN BY CHANGING THE POSITION OF THE SUPPORT?

(4) CAN THE ENDS OF THE BEAM BE RESTRAINED TO DECREASE THE MOMENT?

(5) COULD A PIECE OF STEEL BE NAILED UNDER THE BEAM?

(6) COULD SOLID BRIDGING PROPERLY SPACED AND INSTALLED INCREASE THE BENDING RESISTENCE AND LOWER THE DEFLECTION?

(7) CAN CABLE BE PRESTRESSED AND ATTACHED TO THE BEAM?

(8) IF THE DEFLECTION IS CAUSED BY VIBRATION, CAN THE DEFLECTION BE LOWERED BY: (A) MAKING THE BEAM STIFFER (B) USE A HEAVILY DAMPED MATERIAL (C) DETUNE THE BEAM THROUGH DESIGN.

(9) CAN A NEW TYPE OF PATENTED STEEL OR WOOD BEAM BE USED?

GIVEN

(1) THE LENGTH OF THE SPAN IS GIVEN.
(2) THE LOADING ON THE BEAM IS GIVEN.
(3) THE LIMIT OF DEFLECTION IS GIVEN.
(4) A TIGHT TIME SCHEDULE IS GIVEN.
(5) THE BEAM IS IN A HOUSE IN A REMOTE AREA.

KNOWN

(1) THE STRESSES IN THE BEAM CAN BE CALCULATED.
(2) METHODS FOR COMPUTING DEFLECTIONS KNOWN.
(3) THE TIME ELEMENT LISTED ABOVE IN "GIVEN" WILL EFFECT MOST OF THE POINTS IN THE ANALYSIS.
(4) THE LIMITATION IN COST WILL EFFECT EVERYTHING.
(5) BUILDING IN A REMOTE AREA WILL EFFECT COST AS THE PROPER LABOR MAY NOT BE AVAILABLE.

BEAM DESIGNED

(1) NO, WOOD DOES NOT HAVE TO BE USED BUT A CHANGE MAY RAISE COST BY USING EXPENSIVE MATERIAL - EXPENSIVE METHODS OF MANUFACTURING OR EXPENSIVE MEANS OF INSTALLATION.

(2) IN HOUSE CONSTRUCTION WOOD BEAMS ARE USUALLY LESS EXPENSIVE THAN COMPOSITES, BUT IT MAY BE NECESSARY TO MEET COST AND DEFLECTION REQUIREMENTS.

(3) A CANTILEVER AT ONE OR BOTH ENDS COULD REDUCE THE MOMENT BUT IT MAY CAUSE DEFLECTION PROBLEMS UNDER VIBRATION.

(4) IF THE LONG BEAM IS MOUNTED OVER THE MAIN STEEL BEAM IN THE HOUSE, THERE ARE USUALLY OTHER BEAMS COMING FROM THE OTHER SIDE OR A CONTINUOUS BEAM COULD BE MOUNTED OVER THE SUPPORT. AVAILABILITY AND TIME ARE OTHER FACTORS TO CONSIDER.

(5) THE STEEL COULD BE USED TO CUT DEFLECTION BUT IT IS MORE EXPENSIVE THAN A STRAIGHT WOOD BEAM, BUT IT MAY BE NECESSARY

(6) SOLID BRIDGING IS INDEED STIFFER IF BIG HOLES LIKE HEATING DUCTS ARE NOT CUT THROUGH THE BEAM.

(7) CABLE CAN BE USED BUT IT IS EXPENSIVEE TO INSTALL.

(8) VIBRATION MAY NOT BE CRITICAL BUT IF IS THEN ONE OR MORE OF THE SUGGESTIONS SHOULD BE APPLIED.

(9) ALL OF THE "PATENTED SPECIALS" HAVE A CATALOG LISTING THE PERFORMANCE VERSUS THE COST. OTHER QUESTIONS MUST BE ANSWERED SUCH AS WHO IS GOING TO MAKE IT AND WHO IS GOING TO INSTALL IT.

Figure 2. Retroductive (ball-park) design.

Remember that principles are not chosen to strangle thinking, but merely to give the thinking order and help the thinker reach his conclusion without wasting time. Next, consider the efficient cause: Who designed it, who installed it, or who manufactured it? Last, consider the formal cause, which is the method or form in which the beam is designed to solve the final cause. The form is not necessarily the geometric form, but it includes any way the materials can be put together to satisfy the final cause.

Now let us return to Figure 2. The nine questions on the left are known as the analysis of the concept—a logical analysis, not a mathematical analysis. These questions dissect all of the possible concepts that could make up the final cause. Concept in the logical sense is not the wood or concrete, but represents all of the ideas that could make the beam either wood or concrete. Thus, to address the concept of stiffness in the beam, visualize wood bending and reinforced concrete bending. Analyze each question; determine if it will give you an idea that would aid in producing the final cause.

After you have logically analyzed all the questions, synthesize them (put them back together into one basic concept) with the answers on the right. To arrive at one basic concept, eliminate the questions that do not apply to this problem.

The limited cost will eliminate items 2, 7, and 9, because the cost alone will make these concepts prohibitive. (They could apply to another beam on another day, but not to this beam today.) Item 8 is eliminated because vibration is not given as critical in this case. Item 5 could be kept, but only as a last resort. (It is easy to consider this option because it can be done after everything is in place.) The fact that the new building is in a remote area will further eliminate items 2, 7, and 9.

Retroduction puts the remaining items (1, 3, 4, and 6) into the proper order so that the final cause can be attained. Now we can see that more than one concept will lead to a proper final cause, but retroduction will give at least one good answer, and offers a good method for comparing the alternate solutions.

Determine the single item, of the four left, that must be answered before the others are answered. The answer is to question item 3: "Can the given moment be cut down by changing the position of the supports?" There is no doubt that changing the support position will bring down the moments, but the support may be the outside wall, which may be needed for something other than holding up the beams. Now visualize two extreme solutions: (a) the wall at the extreme end because it is needed there for something else, or (b) the wall moved in to relieve the moments. Remember that answering one question may bring up others that must also be answered. Also, remember that the last question asked is always the first question answered. Follow this procedure to the top of the list in Figure 2.

Your design can now progress with two alternatives, in or out on Question 3. Next, consider item 4: "Can the ends of the beam be restrained to decrease the moment?" Yes, if the beam passes over the central steel beam in the house, it can be nailed to the beam coming from the other direction with little expense. Or, if it is the outside wall, the ends of the beam can be nailed to the wall, which would give it stiffness. Thus, both possibilities are open. Consider item 4 along with item 3. If the cantilever is used, the outside retaining wall cannot be used to support the beam in bending 4 because they don't meet. You need not make this decision yet, but remember that there are two decisions to item 4 and two decisions to item 3.

The next item is 6: "Could solid bridging properly spaced and installed increase the bending resistance and lower the deflection?" The answer is yes, but heating ducts or other pipes cannot go through the solid bridging. There is an alternate solution here—ducts or no ducts.

The last item is 1: "Does the beam have to be wood?" In a remote area, wood is often the only material that is available for such a job.

The order is now established. First, consider item 3, then items 4, 6, and 1. If all solutions like it will not work, item 5 could be considered as a possible addition. The final cause is reached—it is not a single physical piece of wood, but a piece of wood with the right support either on the end or about one third from the end; the beam either attached to either end or both, depending on the supports; solid bridging or no solid bridging, depending on the ducts, etc., and finally a piece of wood that will meet all of the requirements, including deflection. This synthesis in retroduction is an abstraction of the beam, the kind of beam that will meet the final cause needed. (An abstraction is the drawing out from all of the parts and characteristics of a beam the *essential things* that make up the desired final cause.) In this case, all of the questions and answers and the analysis and synthesis have done just this. You don't have a single physical beam, but you do have a composite of the essential characteristics of a piece of wood that will satisfy the final cause.

The final step is mathematical analysis. With mathematics, it is possible to calculate the exact bending moment and deflection in a cantilever, compared to a single span. The same is true with the ability of mathematical analysis to calculate the value of restraining the beam on one or both ends. Thus, you can use mathematical analysis to optimize the many variations discovered through retroduction and select the most efficient beam. You must keep other constraints, such as the outside wall and heating ducts, in mind.

On another day, a similar problem may arise, and the final beam may not be the same, but you can use the *same abstraction to arrive at another beam.* This is the big advantage of retroduction; it is difficult the first time it is attempted, but with a little experience, you can select the designs more and more quickly. Most good designers perform retroduction without realizing it.

This problem would be far more complex if the design were to be used in the middle of a large city where all types of manufacturing methods are available, all types of skilled labor are available, all types of materials are easily procured, etc. Rather than comparing the final four items above, then, you might need to arrive at a single abstraction of the beam by considering all nine items. This is not too difficult if you use a system such as retroduction to list the questions to be answered. No matter what questions you ask, you can answer them for the general case, and you can synthesize this general case and abstract a single "ball-park" of the beam.

A unique ability of the human intellect (to abstract) is well illustrated with this problem. The computer is able to list the *Given* and *Known* items and to ask a series of "canned" questions. But the computer cannot abstract (synthesize) all of these answers into a single abstraction, a final cause. One basic reason is that the memory of the computer is simply a file drawer memory. If you signal the computer for a piece of information, such as a mathematical analysis for the beam, the computer can come up with that analysis. It is a particular thing that can be recalled by finding a code number to call it out. In the process of retroduction and synthesis, however, the memory has to include association of ideas. In other words, only a human memory can be used for the association of ideas. If someone asked you how to bake a cake, you may not remember. But your memory can take you back to the last time that you baked one, and then you can remember all of the problems associated with it, as well as the comments of those who ate it. You remember how to fix it and how to modify it to fit the final cause—a good baked cake.

This idea of abstraction is little understood today, and it should be thoroughly understood by engineers and scientists who work on design and research projects. One such case is the reason why bolts and nuts back off during vibration. The same approach that was used in the beam design is applied to the bolt vibration problem.

The same definitions used in the selection of a beam are applied to the basic research of how bolts and nuts vibrate apart. Certain items are given and known. The final cause is known: "Why bolts and nuts vibrate apart." The system of dialectics used in retroduction is followed through to pose logical questions necessary for arriving at that final cause. The questions are based on the material cause, the efficient cause, and the formal cause. Abstraction is used through synthesis of the logical analysis to arrive at the final cause. (We visualize the nut backing off the bolt.)

The same method, but the individual points listed above, are defined differently for research than those definitions used in engineering design:

First

In the beam problem, the mathematical analysis for the deflection of the beam was known and was listed as *Known*. In basic research, such as in the backing off of a bolt, no mathematical analysis is available.

Second

The time element is the most important element in the design of a beam. It controls the entire design. In basic research, we do not know how long it will take to come up with an answer. This entire study of bolts and nuts could be more a matter of finding out a good course of action to follow first. The actual labor would then take much less time than is spent trying to find the answer. Early in research, the time element should not be our primary concern.

Third

We must consider cost carefully; if we make a career of the problem, the cost will be prohibitive. But, if the cost limitation is too small, secondary results will give only partial answers and, in some cases, the wrong answers. In beam design, we can come up with an answer in 24 hours by retroduction. It may not be the best answer, but it meets the time schedule and the requirements. For bolts and nuts, retroduction may not supply an answer in 24 hours, but it does give an orderly procedure that can be used to consider all the dialectic questions necessary for solving that problem. We can use partial answers to solve part of the problem with the assurance that the results are correct for that part.

KNOWN ITEMS

Known from its definition comes from our experience as a designer, and includes all of the references and reports of the past. However, these *Known* items must pertain to this problem, and we must know that they apply to this problem from our past experiences. *Known* items include methods of research, procedures, danger points, directions from past study outlines, etc. In the design of a beam, the *Known* items are mathematical equations, etc. In the research of bolts and nuts, the *Known* items are principles to use in solving research problems like this one–principles that have been tried, used, and proved in other forms of engineering research. They are not mathematical equations because there is no known equation that describes how a nut backs off a bolt. As designers, we must follow these steps:

1. Determine what happens to a normal bolt before studying exotics and special types of locking devices. In this way, we can establish a standard. Further, we will have a good indication as to whether we need a locking device. Present dynamic testing machines are mechanical and quite violent. They give a good example of this type of load, but do not indicate what will happen under normal conditions.

2. Start with low-vibration loads and build up until the bolt backs off. In this way, we can determine the time threshold of backing off for many sizes of bolts and many loading conditions. Although this task is slow and exacting at first, we can use it later to give direction to the remaining dialectic decisions.

3. From past experience, establish standard input wave patterns for testing. To compare many different sizes and shapes, we must establish a standard input wave pattern and

check this wave pattern from time to time to ensure that such things as machine wear do not change the type of tests.

4. Early in the testing program, establish a series of structures that can be used to test the bolts. We can change the waveform by the holding fixture. Such items as frame stiffness, clamping stiffness, workmanship, and methods of design and assembly could affect the input waveform from the testing machine to the bolt.

5. Force depends on acceleration and only partially on displacement (F = ma). The time function in the force input is important; it can vary all the way from a square wave to a perfect sine input. We will study the waveform as a function of acceleration. Displacement is useful, but it doesn't tell the entire story. This does not mean that an inexpensive machine could not be used to run the tests later, but early in the testing, we must establish what conditions cause nuts to back off bolts. A worn machine can cause a complete change in waveform.

6. Throughout the testing, constantly look for ways to use the testing to prove the dialectic questions. Perhaps we may use mathematical analysis to check the dialectic questioning and answers, or use a combination of testing and analysis.

7. Remember that it is better to *know one part of the program well and with assurance* than to give a hopeful all-encompassing solution that has to be constantly modified for verification. Although this may slow testing in the beginning, it will pick up as time progresses and, most important, it gives accuracy to the program.

8. Attempt to work with existing testing machines and data reduction methods as much as possible. This effort will permit greater program reliability, particularly in the input curves, and will further act as a check on other tests performed in the field, either verifying or negating them.

9. Search the research field of past and existing programs that involved vibration work. This search can lead to help beyond the study of bolts and nuts. Other forms of hardware, such as couplings and universal joints, have exhibited similar problems over the past years.

GIVEN ITEMS

The items in the *Given* column are also different from those for the design of the beam. In the beam problem, the *Given* items were specific physical items that could be attained by mathematical analysis. In research, these items are not known; the *Given* items come directly from the committee that was set up to study this problem.

Testing and further analysis may either prove helpful or change the tone of some of these items *Given*, but the American Society of Mechanical Engineers (ASME) Committee on the Loosening Mechanisms of Bolts and Nuts has established standards for beginning the program. The points presented by Dr. Peter Zemanick, chairman of the ASME Committee, are representative of recommendations received on how to improve a proposed research program on bolt loosening and make it more practical. These representative remarks came from engineers and scientists familiar with the field–men who know the past problems and programs of similar nature.

In beam design, the *Given* items are specific, such as the length and load on the beam. In basic research, the *Given* items are those that are desired, with indications on the way these items could be approached. The *Given* items, in order, are:

1. Define loosening.
2. Define the loading of primary interest as transverse (clamped part loading or movement tending to "shear" the bolt; transverse slip between the clamped parts).
3. Define the bolt-size range of interest (diameter).
4. Define the generic point of primary interest (bolt and nut, two clamped parts, rigid relative to the bolt axial stiffness).
5. Define the dynamics of the intended loading.
6. Work to sharpen the statement of objectives.

In both the design of a beam and the backing off of the nut, the final cause is specific: "The beam designed" or "Nuts or bolts vibrate off." The material cause in both cases was usually sought first. For the beam, the first question was, "Does the beam have to be wood?" In the vibration of bolts, the Committee wants a certain size to be established early, and this would include the material used. The formal and efficient causes were listed and solved directly in beam design, but in research, the only stipulations are goals to look for when seeking the answer. For instance, we must first study the horizontal shear across the bolt. This is an efficient cause; the motion is the agent that will back the bolt off. The formal cause is there by implication: it simply states that a bolt that is held together in a certain manner is in such a form that the horizontal shear will cause the nut to back off. The idea in research is to get as many forms of material as possible to cover the entire field and come up with a few forms that, by their very nature, will cause bolts to back off. These are guides and directions and not specific pieces of hardware to use to get the bolt in direct shear. The dialectic questions will bring out the specifics.

DIALECTIC QUESTIONS

In research, the dialectic questions are far more difficult to attain than those in the design of a beam. In the design of a beam, the paths to the final cause are well marked with handbook suggestions. In basic research such as the backing off of nuts from the bolt, however, the questions are not well defined. Our questions must follow the *Given* and *Known* and they should all answer the three causes–the material cause, the efficient cause, and the formal cause. If we had no experience, research would be impossible. And, regardless of our experience, the research would be very time-consuming if the Committee had not established the *Given*. The following are the dialectic questions we must address:

1. What motions of the structures holding the bolts can cause the bolts to back off?
2. What are the forms of the structures used to hold the bolts?
3. What is the effect of lubrication on the threads?
4. How could the entire structure with bolts be tested?
5. While studying the many loads that could be applied to the bolts from the structure, is it possible to break down the loads into several different types of testing and evaluation?
6. What available vibration testing machines would be most desirable for testing bolts and nuts? What static testing machines?
7. What methods are available for measuring the exact moment that the nut begins to back off the bolt?
8. What are the effects of boundary conditions on the frames that are bolted together? What about the friction constant?
9. What types of vibration loads can be analyzed? What kind of tests can be performed to correlate with analytical techniques?
10. How are thread-locking devices evaluated?
11. How are secondary dynamic effects taken care of?
12. Is embedding a problem?
13. What is the load distribution on the threads?
14. How important is preload and how is it measured?
15. How important is a series of torquing, loading, unloading, torquing, loading, and unloading?
16. How many tests are necessary to establish a reliable trend or to bring the testing to a point of mathematical analysis?
17. What is the effect of the size of the bolt and nut?
18. What is the effect of the geometry of the threads?
19. What is the effect of multibolt configurations?
20. What is the effect of steady-state loads on top of vibration?
21. How is waveform analysis measured in the field, and how is it transferred to a testing machine?

ANSWERS TO DIALECTIC QUESTIONS

In the beam design, most of our answers came from past experience or from the manufacturer's handbooks. In basic research such as this bolt and nut study, many of the answers to the dialectic questions are in the form of abstractions. Some of the answers are direct and can be answered from handbooks, etc., but these can lead to difficulties because the simple answers must be modified by the *Given* and *Known*.

Let us discuss Question 5 first to illustrate the importance of abstracting individual answers to the dialectic questions: "While studying the many loads that could be applied to the bolts from the structure, is it possible to break down the loads into several different types of testing and evaluation?" Books have been written on this subject. There are far too many loads for totalling and arriving at an average cross section. Instead, we must abstract all the loads that apply to bolts and nuts the loads that would cause the nuts to back off. While making the abstraction, we must keep the *Given* and *Known* items in mind, as well as the cause that is used to set up Question 5. The cause is related to the efficient cause: it is the vibration that directly causes the nuts to back off the bolts. Thus, the vibration loads attribute directly to the efficient cause. Of these conditions, the abstraction used by the Goddard Space Flight Center (GSFC) in studying structures that would cause nuts to back off bolts is as good as any (reference 3, GSFC Specification for Vibration Structures). This specification calls for dynamic loads of sine, random, noise, shock transients, and steady-state loads. Testing laboratories throughout the world consider the sine of Figure 3 and the random of Figure 4 to be the most important. Noise could be included as a form of random vibration testing on a structure as is easily demonstrated by observing noise loads on structures. Shock loads include many kinds of shocks too numerous to list (Figure 5). However, these shocks are reduced to random if the bolt is remote from the point of impact.

To answer this question, we needed a thorough knowledge of the field of structural dynamics, as well as what kinds of loads get to bolts in a structure. We then needed to simulate these load conditions in a laboratory. From this background of knowledge, we could abstract the essential characteristics of all these types of waveforms to give a brief review of the many loads on bolts each year.

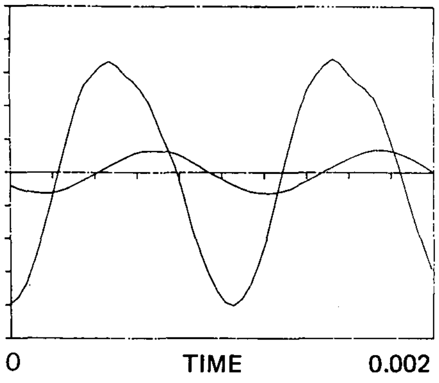


Figure 3. Sine and resonance.

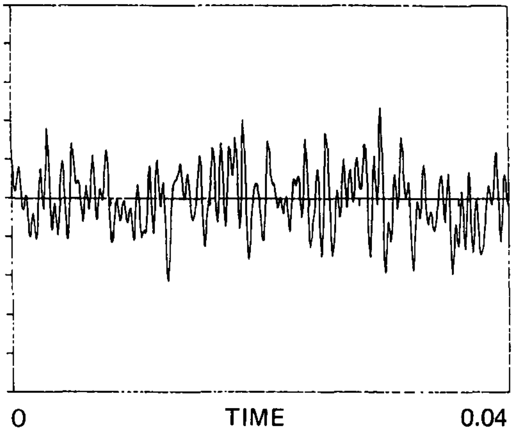


Figure 4. Random vibration.

That this is not a mathematical average but an evaluation of the essential characteristics makes it an abstraction.

Let us address all 22 questions, relaying on abstraction as we did in answering Question 5.

Question 1: What motions of the structures holding the bolts can cause the bolts to back off?

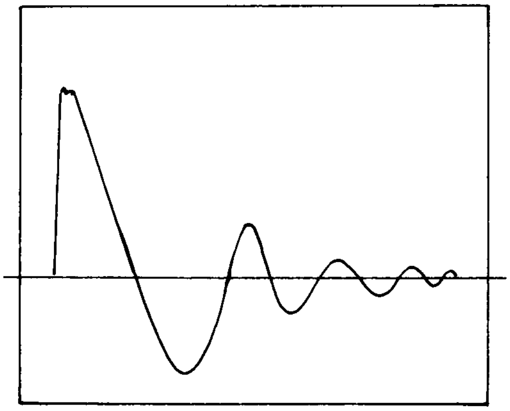


Figure 5. Transient response to shock.

There are numerous answers to this question. However, the Committee has stated in the *Given* or direction of study that the shearing force across the bolt is known from experience to cause more harm than anything else (reference 4). It is true that tension loads can cause a shearing action on the threads by a barreling of nut under tension. This barreling is the opening and closing of the circle of the nut diameter. According to our *Known* items, one principle that was established early in the study was that it would be better to first solve a small part of the problem well and then branch out later. Because the *Given* states that the horizontal action comes first, we will study it first.

Question 2: What are the forms of structures used to hold the bolts?

After we have determined, through abstraction, that horizontal shear is the primary cause of bolts vibrating off, the next logical abstraction is to determine the type of structure that would put direct shear on the bolt. Bear in mind that it is most desirable, if possible, to make a model that has shear only, and not bending, tension, or compression on the bolt. Thus, the first model, pictured in Figures 6 and 7 will put pure shear on the bolt. This abstraction takes experience. Houses, cars, airplanes, and appliances have to be mentally abstracted to visualize the forces on all of these structures simultaneously. Then the structures that produce a high percentage of horizontal shear are abstracted from the test. Next, from all of these structures a simple model is made to simulate the type of structures that have this kind of horizontal shear load. Figure 6 is one example.

Figures 8 and 9 illustrate the next abstraction. This bolt involves a combination of shear and bending. However, because of the way the model is made, the bending load on the bolt can be kept very low (to less than 10 percent). Figures 10 and 11 show the same configuration with a thinner model. In this model, the end tends to rotate and induce a severe bending and eventual tension load through prying, which could eventually cause the shear load to be less than 10 percent of the initial load on the bolt. This model could produce the opposite effect to that intended by this study. The first part of this study is to look for *pure shear* on the bolts.

We can argue that the load in Figure 10 is more indicative of what can happen in actual true-life situations. However, if we solve the case of Figure 10, we know what happens in that individual case, but we can not abstract and apply it to other cases because we can not separate shearing forces

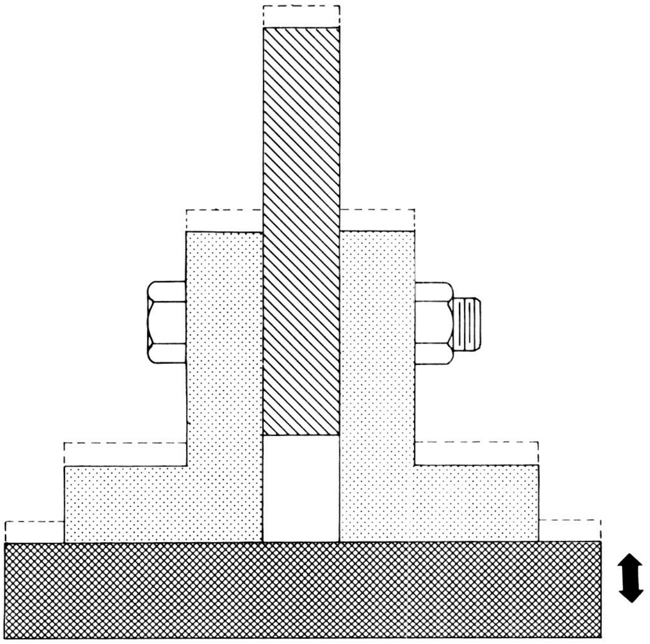


Figure 6. Inertial load (double shear).

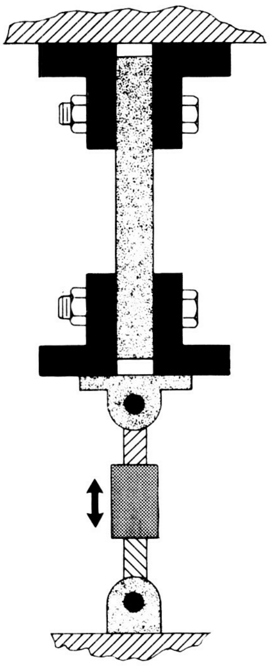


Figure 7. Direct load (double shear).

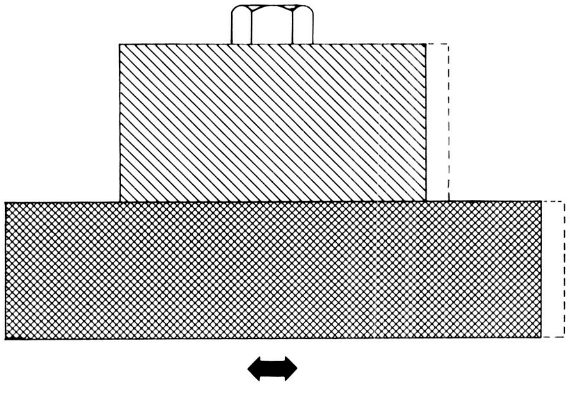


Figure 8. Inertial load (single shear).

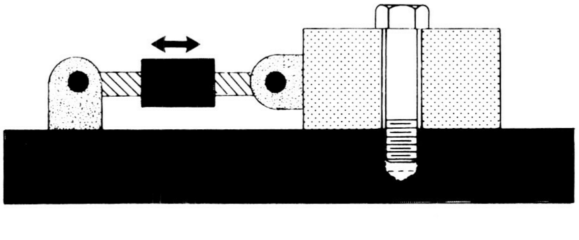


Figure 9. Direct load (single shear).

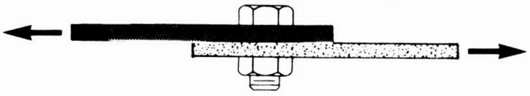


Figure 10. Single shear before loading.

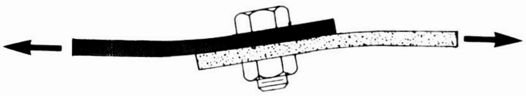


Figure 11. Single shear after loading.

from prying and bending forces. If we use the model of Figure 8, the result could be universal and would apply to all forms for which shear is the prime cause of bolt backoff. There is nothing wrong with special-case studies (Figure 11), but the purpose of the study from the *Given* and *Known* is to define the terms that would give universal results early in the study. Special cases can be taken later. Furthermore, the study of Figure 8 will make it easier to study Figure 10. Only through abstraction can these models can be designed to give the desired loads specified in the *Given* and *Known*.

For our next abstraction, let us make a model which would cause the shear to occur as a *result* of bending. (See Figures 12 and 13.) This type of structure is the most common for causing shear loading on a bolt. It includes the joints and panels of most major buildings, aircraft, cars, homes, and household utilities. When a car goes down the road, the vibration comes from the spring and shocks. If there are potholes or swells in the road, these loads transfer themselves to the car through inertia loads in the frame, and cause bending in the frame. These bending frames and panels are held at the edges, and as they bend, they cause a shearing action at these corners. This is not the same type of load as that shown in Figure 14, which causes shear by prying. Although the load shown in Figure 14 is more severe, it is not nearly as common as those shown in Figures 12 and 13.

Finally, a basic and fundamentally common load on bolts is pure tension (Figures 15 and 16), but pure tension causes shear by dilation or opening of the nut on the bolt during vibration. As the tension is applied to the nut from the bolt, the diameter of the nut is increased, causing this dilation. As it dilates in and out, it causes a shearing action on the threads, and these shearing forces slide the nut loose. This dilation can cause the nut to back off, but it must be viewed in a completely different abstraction than those for the previous three models. The first phase of the study will therefore *abstract* from all of the models the first three (Figures 6, 8, and 12). We will study Figure 15 later.

Although these basic models are not the only types of models that put only shear on the bolt, they represent over 90 percent of such models. They do not include models that give a combination of shear and bending, tension, or compression, but they are included for the first phase of this study to study the effects of *pure shear at first*.

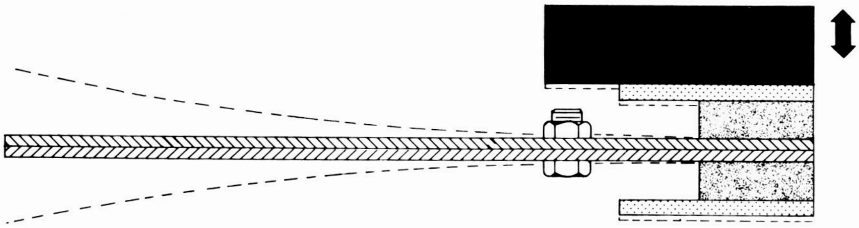


Figure 12. Inertial loading (shear due to bending).

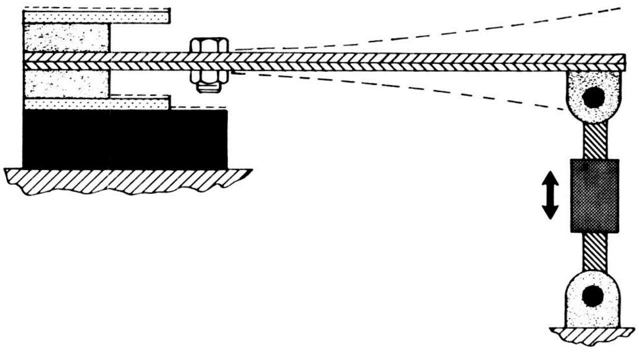


Figure 13. Direct loading (shear due to bending).

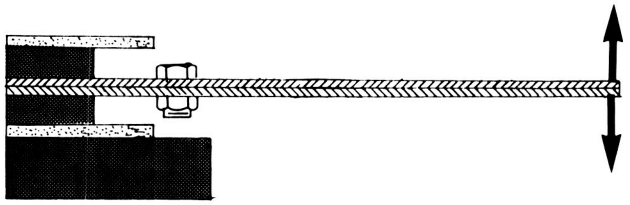


Figure 14. Direct loading (shear and prying).

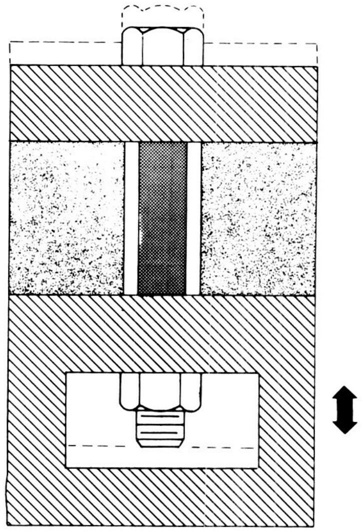


Figure 15. Inertial loading (direct tension).

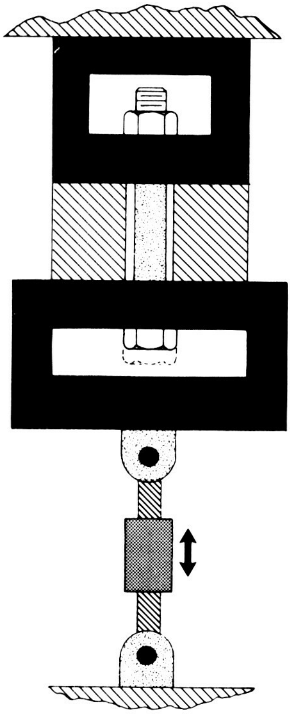


Figure 16. Direct loading (direct tension).

Question 3: What is the effect of lubrication on the threads?

If there is no lubrication, the coefficient of friction ranges from low to very high. This wide variation can cause a change in the clamping force when the bolts are torqued. Also, when a coefficient is high, the frames could start to gap and destroy themselves. If the torque is assumed to be low and then torques very high because the technician thought that it was high, the bolt could be forced into yield and possible destruction.

If the bolt is lubricated, the coefficient of friction is low, and the torques are easier to predict. The initial torquing stress in the bolt is low and does not add materially to the stress condition. Therefore, by abstracting all of these problems and considering the most common thing to do when good torquing is used, we will decide to perform the initial tests with lubricated threads.

Question 4: How could the entire structure with bolts be tested?

During testing, accelerometers can be placed at key places on the large structure. From these accelerometers, the loads on the members can be calculated. After the loads are calculated, the moments and shears can be calculated. From these shear loads, we can resolve the individual loads on the bolts, or we can make a structural mathematical model of the large structure and calculate the shear and bending moments with a system similar to Nastran. After we have calculated the shear loads, we can analyze the moment on the bolt and subsequent shear by equating it to one of the model tests already performed. (See Figures 6 through 16.)

Whether we have a large model or a small model, shear is shear. When we have determined the shearing force causing the bolt to back off, we can analyze any subsequent problem by mathematical analysis. No further testing is necessary.

Question 5: While studying the many loads that could be applied to the bolts from the structure, is it possible to break down the loads into several different types of testing and evaluation?

We must abstract from all of the models (Figures 6 through 16) and, further, we must abstract the various loads on these models. Then, when we have considered all of the structures from automobiles to ships etc., we must abstract from these structures the type of dynamic loading condition that would affect the bolts and cause the nuts to back off.

Initially then, we would perform tests that would simplify the many billions of applications and abstract from them a few models and load forms that would apply to the entire field of bolts and nuts. We can do this by first testing a simple cantilever, which is the simplest form of structure and the easiest to analyze with both mathematical analysis and logical dialectic analysis. When we obtain the results of the cantilever, we can apply the principles learned to more complex structures. The next structure is the bent. (See Figures 44 through 48.)

Question 6: What available vibration testing machines would be most desirable for testing bolts and nuts; What static testing machines would be best?

Early in the study, we cannot use mathematical analysis to verify dialectic reasoning; we must rely on testing. The testing machines should be simple and the waveforms received from these machines should be carefully monitored and studied. Many testing machines provide purely a measure of displacement. Displacement may give certain verifications, but some cannot be determined by a displacement machine. Most displacement machines do not have a well-defined waveform as measured by acceleration, and the force on the nut is given by the inertia equation ($F = ma$), where a is the acceleration and is the best indication of the load on the bolt—not the displacement. The waveform analysis refers to acceleration waveform analysis. Early in the testing, the testing machine is probably the most important tool to be used; nothing can substitute for a good testing machine. (The static machine is much simpler because it measures only the proper deflection and the proper force on the structure.)

Question 7: What methods are available for measuring the exact moment that the nut begins to back off the bolt?

Physical visualization is one method. Another method, found by abstracting the motion of item 2, is to measure the moment when the natural frequency begins to change. This can be done only during sine testing, but it is accurate and consistent. Furthermore, it can be done while the test is in progress and the vibration load continues. By stopping the vibration load and starting it again, the amplitude can be changed and another variable added to the study.

Question 8: What are the effects of boundary conditions on the frames that are bolted together? What about the friction constant between frames?

When two plates are in shear, the coefficient of friction will change the amount of that shear taken by friction. In small shearing forces with large coefficients of friction, the entire load is taken in friction. However, friction is a variable that is hard to describe mathematically. Therefore, early in the study, we must lubricate the surfaces that are held together by the bolts so that a large amount of the shear force goes to the bolt and not to friction.

Question 9: What types of vibration loads can be analyzed? What kind of tests can be performed to correlate with analytical techniques?

If the vibration load is primarily the fundamental load and the displacement can be measured, there should be a direct correlation between the dynamic load and the static load. This point must be proved. Early in the testing, we should determine if the fundamental mode is primarily responsible for the backing off of bolts and nuts.

Question 10: How are thread-locking devices evaluated?

Thread lockers of many types are evaluated by comparison to existing standards or bolts without thread lockers. We can also test the thread lockers to see if they meet a certain specification. If the thread locker meets that specification, it can be specified for that use. We should try to get as few specifications as possible so that we can use a handy reference to see where these thread lockers apply. Because these specifications are closely tied with items 1, 2, and 5, we should abstract all of these items together.

Question 11: How are secondary dynamic effects taken care of?

Most secondary dynamic effects are feedback problems that are common in shock and vibration. An input will cause a member to vibrate, and the vibration will feed back to the input and tend to change the input. We should eliminate this problem early in the study. As the testing progresses, we can introduce and evaluate more complex structures with feedback; but early in the study, we should design simple structures with simple loads to precisely measure the load. We can then make comparisons with other loads and other simple structures. Many of these feedback problems are difficult to handle and they should be handled with both testing and mathematical analysis. Experience is a great help with these problems.

Question 12: Is embedding a problem?

Embedding is a serious problem when the bolt is backing off in shear. In some cases, the embedding prevents the shear and is therefore desirable. Some types of washers use this principle to prevent the bolts from backing off, but in other cases, they do not work. The danger is that the use of the embedding may stop the nut from backing off the first time, but when the nut is turned up again, the surface is uneven, and the clamping torque cannot be controlled. We should avoid these types of variables early in the testing because they are too inconsistent to analyze. They are for particular uses, but they do not have a universal application. Some uses include using the nut without a washer, which presents two serious problems: (1) the embedding will destroy the usefulness of the frame to get a consistent clamping force the second time around and (2) the embedding will cause the bolt to lose its clamping force, and without the clamping force, the embedding may not prevent the nut from backing off.

Question 13: What is the load distribution on the threads?

In a normal nut, the first two threads take more than half the load. When a bolt is torqued to one-half yield, it can be assumed that the first thread has already started to yield. Other variables then enter. Is the nut stronger than the bolt, or is the bolt stronger than the nut? Which is recommended? Our other considerations include clamping force and fracture analysis along with gapping. Early in the study, we should keep the clamping force as low as possible to maintain a stress value in the threads in the linear region. Other problems could result, such as yielding, that would lead to gapping, which could be just as serious as the backing off of the nut. (There are patented devices on the market for keeping the loads on the threads uniform, and these patents should be studied later.)

Question 14: How important is preload, and how is it measured?

The preload is generally measured with a torque wrench; many types and forms of torque wrenches are available. For careful laboratory-controlled conditions (threads as good as class B, clear, straight, and flat clamping plates, good lubrication, and well-calibrated torque wrenches), the torques can be controlled within ±10 to 15 percent. In this way, the preload is predictable considering the accuracy of the tests. In some tests, bolts calibrated with strain gages are used to measure the clamping force at ±5 percent. Load washers and load cells are also used for this work. Ultrasonics offers the most accurate means of measuring preload. Early in the testing, this item should be controlled very closely, and great care should be used to keep this preload consistent and accurate.

Question 15: How important is a series of torquing, loading, unloading, torquing, loading, and unloading?

If the yield of the bolt or the nut is not reached, the continuous torquing should not bother the end result. Some people claim that the second torque is never the same as the first. It could be that part of the assembly is yielding, and if so, this should be determined to make the tests valid. However, in the early part of the testing program, the hardware should be strong enough to circumvent this problem. It can be established later (in the yield region) after standards are established.

Question 16: How many tests are necessary to establish a reliable trend or to bring the testing to a point of mathematical analysis?

This problem cannot be solved until the testing begins. The standard deviation from the mean is the critical item, and it takes testing and plotting to establish this point. The use will determine the accuracy needed, and the tests will give that point.

Mathematical analysis can be used at any time throughout the tests to verify the dialectic reasoning (analysis and synthesis). The ideal study will include both mathematical analysis and testing to verify dialectic questioning.

Question 17: What is the effect of the size of the bolt and nut?

Small bolts require less expensive testing equipment, less expensive testing machines, and inexpensive measuring techniques. We should use them at first to obtain the first principles; later, we can integrate larger bolts into the program. We must take care that the bolts are not too small, because very small bolts make the torquing and measuring less accurate. Bolts about 0.25 inch in diameter are about the right size for preliminary testing.

Question 18: What is the effect of geometry on the threads?

Most threads in the United States are 60-degree threads, and most specifications are written around this type of thread. In the preliminary study, we should begin with this type of thread because over 90 percent of existing threads are 60-degree threads. We can test other degrees and exotics later.

Question 19: What is the effect of multibolt configurations?

Multibolt combinations are far more complex, and they offer many challenging problems, many of which have not been solved to this day. Static analysis is difficult enough, but dynamic analysis of multibolt situations is even more complex, and a number of measuring positions are required to pick up the motions. Unfortunately, the loosening of one bolt immediately throws extra loads onto the other bolts and causes a different load pattern to the remaining bolts. These types of bolt patterns are critical and will eventually have to be analyzed. Early in the program, we should test single bolts to establish certain principles. When we have determined these principles, we can apply them to the analysis of complex systems.

Question 20: What is the effect of steady-state loads on top of vibration?

This variable could affect the rate at which nuts vibrate loose of bolts. Previous tests indicate that the steady-state load can add to the preload. This extra load can throw the threads into the yield region, and thereby loosen the clamping force. With a reduced clamping force, the nuts and bolts may come apart sooner. We can determine this from testing, but we should do it only after we have confirmed the fundamental principles.

Question 21: How is waveform analysis measured in the field, and how is it transferred to a testing machine?

A considerable amount of data on this type of load evaluation is available to research. It is possible today to tape a load in the field and play back that load to a model in the laboratory to study the exact condition of motions. This procedure, which concludes the synthesis of the individual questions posed in the analysis, should be added to the program after the fundamental principles are confirmed. Some of the answers are straightforward from past experience or handbooks, some have to be abstracted to synthesize data too voluminous to be analyzed mathematically.

Next, we should synthesize all of these answers to the dialectic questions and abstract from them a single concept that we can test or analyze. As we answer the individual questions, it became obvious that the complete solution to the problem will not become available until we have synthesized and tested a series of abstractions of individual groups of answers.

Our first test is to eliminate the variables that we can study after we have established the fundamental principles. Rather than go through all of these items, let us look at the answers to the dialectic questions and form a synthesis of any group of these points to come to a definite conclusion immediately. (Remember that, when this study began, the items known were principles. If any of these principles could be proved in a few simple tests, we should use these principles to further the study. Perhaps some of these principles could be wrong for this type of research, and we can determine this by working one form of synthesis through to a single abstraction.)

Abstracting the necessary items for a valid testing program from the 21 variables listed indicates that the following are necessary for a starting program: items 1, 2, 3, 5, 6, 7, 9, 14, 15, 16, and 18. Next, we list these 11 items and abstract the order necessary for completing a successful testing program. As we abstract these points, we consider only some of the dialectic answers, for example, item 6 asks: "What available vibration testing machines would be most desirable for testing bolts and nuts?" This question would involve many machines, but in abstracting the many machines available, certain principles stand out immediately:

1. The machine should be easily available to others in the field.
2. The machine should be able to handle many waveforms, such as sine and random.
3. The machine should be able to reproduce the same outputs from day to day without change (electromagnetic shakers).
4. The machine should be able to produce a waveform that can put only a shearing force, and nothing else, on the bolt.
5. The machine should have instrumentation that shows the inputs to the testing fixture and the response of the testing fixture at the bolt tested. If the waveforms are not available, others doing the same work will have trouble reproducing the data.

The answer to these principles is an electromagnetic machine that is large enough that the feedback of the testing fixture to the machine will not change the input waveform. The testing machine should therefore be more than 10 times heavier than the testing fixture, and it should be stiff enough to keep individual parts of that machine from resonating. Mechanical machines have irregular waveform inputs, which rules out their use because the work is not completely reproducible.

Item 2 listed the many forms of fixtures that could be used to put shear on a bolt. Figure 6 was chosen because Haviland (reference 4) had used this fixture and proved its usefulness for giving a shear load on the bolt. Furthermore, in conjunction with item 6, this fixture can produce a fundamental waveform on the bolt without feedback or secondary motions caused by other members of the structure. We must consider all of these items carefully early in the testing or our results will not show exactly what caused the motion and what effect it had on the fixture. We can determine the exact load on the bolt, and we can perform a mathematical analytical study to apply these forces to other bolts and other frames.

Item 3 asks the question about lubrication. Previous work performed by the Bureau of Standards and others demonstrate that reliable results can be obtained only when the threads are lubricated. Later, it may be necessary to include nonlubricated bolts and nuts, but early in the testing, we should begin with lubrication because this will give a consistent value to the study.

Question 1 lists horizontal shear on the bolt as the most probable cause for the nut backing off the bolt. The Committee listed this opinion in its *Given*; the group agrees that this type of loading should be studied first. Other forms of loads can be studied later, but the study begins with the motion that is most probable for coming up with a conclusion.

Question 5 is the type of load to be put on the bolt that will result in horizontal shear across the bolt. This item was discussed previously in setting up the dialectic questions, and it was decided that sine and random testing would best describe more than 90 percent of the loads that cause horizontal shear on bolts.

Question 7 is used to determine the exact moment that the nut begins to back off the bolt. Early in the tests, it was decided that as many methods should be used as possible. Visible backing off and the change in natural frequency will be used. The measuring of torque will be used from time to time to check these measurements.

Question 9 asks what can be mathematically analyzed. There are so many ways that this lead could be shown in a research program that it will have to wait until the first series of tests are performed to find out if many of the tests can be eliminated by using mathematical analysis. In the design of the beam in the house, the entire abstraction was done before mathematical analysis was performed. The ball-park answer was found with the first analysis.

Question 14 asks how important preload is. It is most important, and it will be assumed, early in the testing, that the preload is a function of torquing. As the torquing decreases, so will the preload.

Question 15 is a question about repeated loads. This question will be addressed early in the testing to ensure that one test is not just an odd element. The tests, then, should be performed in such a way that this repeated load pattern can be performed.

Question 16 asks how many tests will be required before a trend can be established. This question will have to be answered when the tests begin. The results could be so random that the method would have to be abandoned. However, a consistent pattern of results early in the testing will lead to good mathematical analysis.

Question 18 is designed to establish the angle of the thread. Over 90 percent of the threads in the United States are 60-degree threads, so this angle will be studied first and variations will be studied later.

PRETEST STUDY

Now let us consider all of the dialectic questions and the *Given* and *Known* items to determine exactly where they stand. The dialectic questions should include the *Known* items because these are principles that must be verified. Furthermore, the *Given* items of the committee must be included in the questions to verify these assumptions.

Figure 17 is a summary of the entire system of retroduction. In the upper left, we begin with the thing sought—either a design of a beam or why bolts and nuts vibrate apart. The lower left lists the *Given* directions from the committee. The lower right list lists the *Known* from past experience or handbooks. The goal is listed in the upper right. It is either the designed beam or the nut vibrating off the bolt. Next, the dialectic questions are posed and listed. Thus, we develop individual answers to the questions, keeping in mind the *Given* and *Known*. Furthermore, we include the four causes when answering the questions.

Finally, at the bottom center is the position that we now hold in the vibration of nuts off bolts. We have eliminated the items that are of no concern early in the testing. Next, we will list in the proper order the remaining items that we must consider. Figure 17 shows the precise moment in this

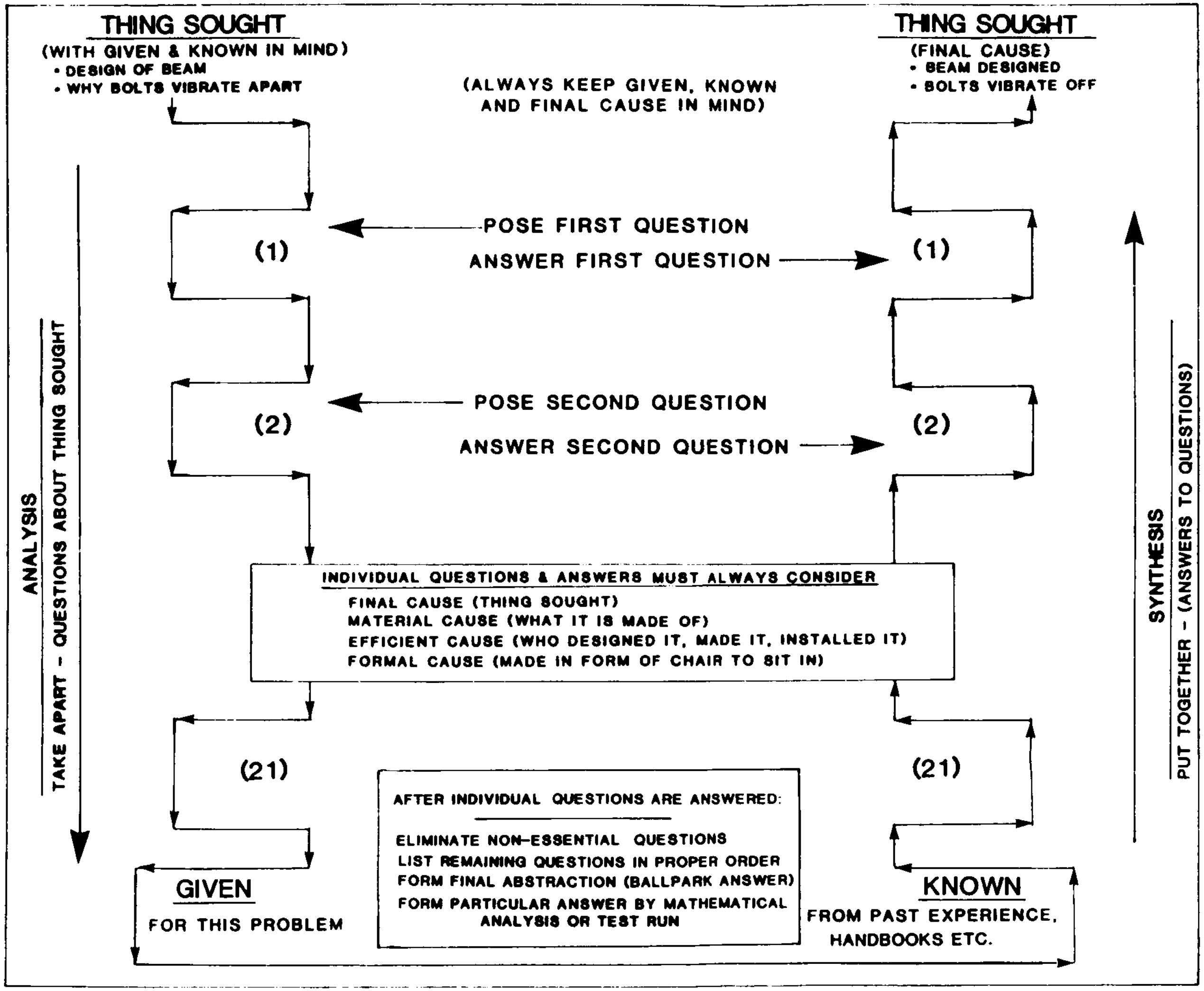


Figure 17. Retroduction (general application to design and research).

study. We eliminate the dialectic questions and list those that remain (the *Given* and *Known*). At the bottom of the list we will consider those items that must be decided after the tests are started: items 9, 14, and 16.

Next, we will list the items that have been determined from our dialectic reasoning: items 3, 6, 7, and 15. The remaining items are 1, 2, 5, 9, and 18. (The order is now established, and it is presented in Figure 18.) Item 18–the 60-degree thread–is first. Items 1 and 2 are considered next–the type of structure that would put shear on the thread and the direct and indirect type of loading. In other words, the fixture will determine the shear on the bolt and, at the same time, determine whether the load is direct or inertial. Next, we will consider the actual testing of item 5. These loads will be sine and random vibration testing. Finally, we will consider methods of mathematical analysis for coordinating testing with this mathematical analysis and dialectic analysis with mathematical analysis (item 9). These dialectic questions have been ordered so that this can be done, and it will be illustrated after the test report.

The following summarizes the action taken:

1. The committee established the items *Given.*
2. Listed are the items *Known* from past experience and handbooks.
3. The dialectic questions are posed that would answer the material, efficient, and formal causes.
4. The answers to the individual questions were found by abstraction or by past handbook knowledge.
5. All of these items–*Given*, *Known*, and dialectic analysis–are listed and from them are abstracted the essential steps to be taken in order:

    a. Nonessential items left out at first.

    b. Certain variables fixed for the first steps.

    c. The order of study and testing set up into a synthesis as listed in Figure 19.

    Figure 19 illustrates the first synthesis of the unknown terms that were actually tested. The object of the tests was to find a number of questions which could be answered, though they be few.

    Dialectic Question 3 was answered first. Tests at the Bureau of Standards and elsewhere showed that consistent tests would not result if the threads were not lubricated. Thus, Question 3 was answered.

    Question 18 was answered next. It is known that over 90% of the bolts under study have a 60-degree angle on the threads. On the diagram (Figure 19), this 90% is represented on the top of the graph. It is impossible to test more than one thread shape at

DIALECTIC QUESTIONS

1. What motions of the structures holding the bolts can cause the bolts to back off?
2. What are the forms of the structures used to hold the bolts?
3. What is the effect of lubrication on the threads?
5. While studying the many loads that could be applied to the bolts from the structure, is it possible to break down the loads into several different types of testing and evaluation?
6. What available vibration testing machines would be most desirable for testing bolts and nuts? What static testing machines?
7. What methods are available for measuring the exact moment that the nut begins to back off the bolt?
9. What types of vibration loads can be analyzed? What kind of tests can be performed to correlate with analytical techniques?
14. How important is preload, and how is it measured?
15. How important is a series of torquing, loading, unloading, torquing, loading, and unloading?
16. How many tests are necessary to establish a reliable trend or to bring the testing to a point of mathematical analysis?
18. What is the effect of the geometry of the threads?

GIVEN

1. Define loosening.
2. Define the loading of primary interest as transverse (clamped part loading or movement tending to "shear" the bolt, transverse slip between the clamped parts).
3. Define the bolt size range or interest (diameter).
4. Define the generic point of primary interest (bolt and nut, two clamped parts, rigid relative to the bolt axial stiffness).
5. Define the dynamics of the intended loading.
6. Work to sharpen the statement of objectives.

KNOWN

1. Determine what happens to a normal bolt before studying exotics and special types of locking devices . . . .
2. Start with low-vibration loads and build up until the bolt backs off. In this way, a time threshold of backing . . . .
3. Establish standard input wave patterns for testing, from past experience. In order to compare many different . . . .
4. Establish early in the testing program a series of structures that can be used to test the bolts . . . .
5. Force depends on acceleration and only partially on displacement (F = ma). The time function in the force input is important. It can vary all the way from a . . . .
6. Throughout the testing, constantly look for ways that the testing could be used as a proof of the dialectic . . . .
7. It is better to *know one part of the program well and with assurance* than to give a hopeful all-encompassing solution . .
8. Attempt to work with existing testing machines and data . . .
9. Search the research field of past and existing programs engaged in vibration work. This can lead to help . . . .

Figure 18. Retroduction applied to research (why nuts back off during vibration).

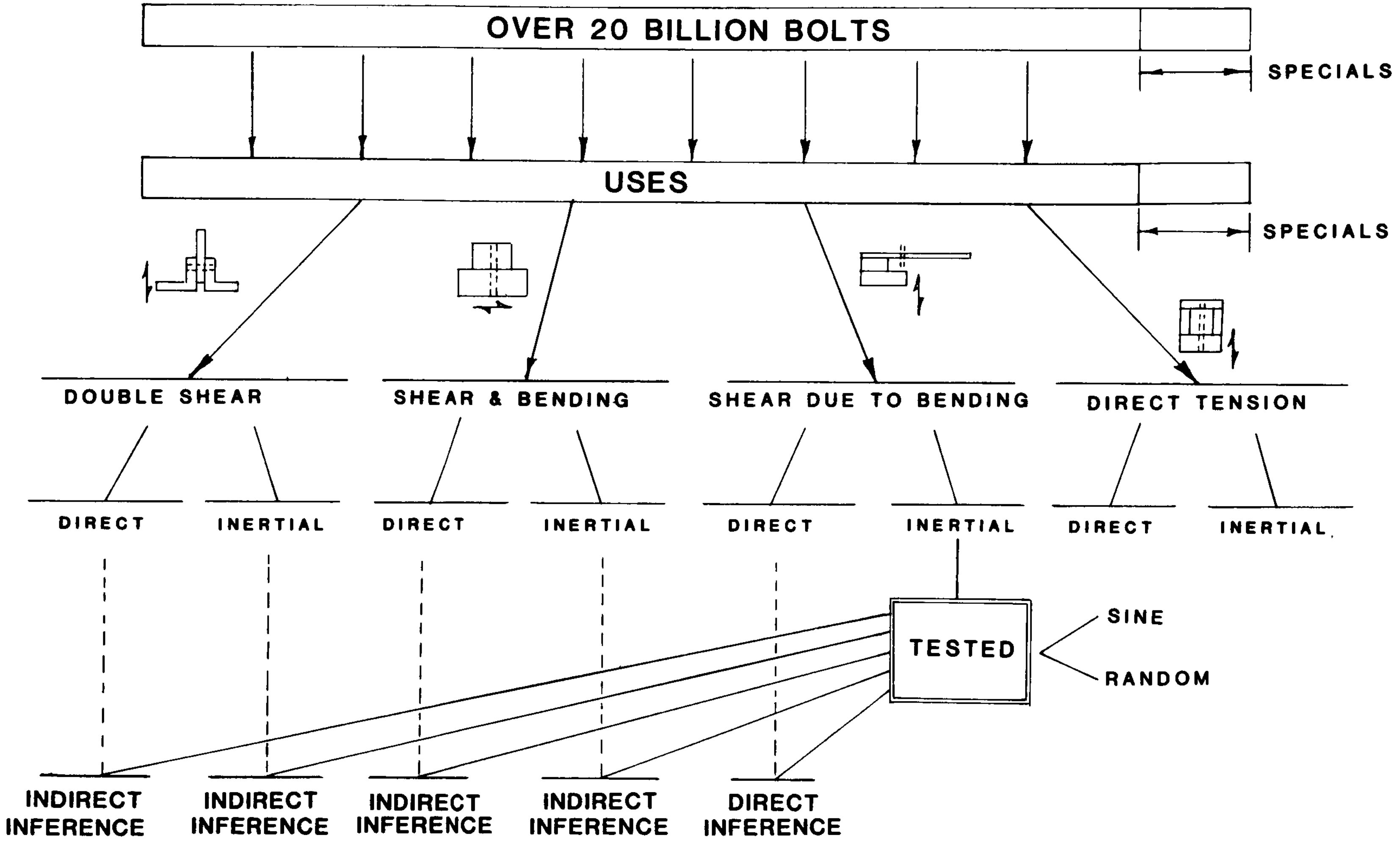


Figure 19. Results of first phase of bolt vibration tests.

a time. The 60-degree thread was chosen because it represented a vast majority of all bolts used in the United States. The small number of other bolts can be tested later.

On the next graph (Figure 19), the number of general configurations are shown that could represent a typical bolt in pure shear. This is the answer to Question 2. Again, these models do not represent all of the figures that could produce pure shear in a bolt, but they represent over 90% of these figures.

Note that the tests were listed in Figure 19 as sine and random. Sine and random testing answers Questions 5. These are not all of the loads but they represent a vast majority of these vibration loads which cause nuts to back off bolts.

Part of Question 5 is to anticipate the loads as being either direct or inertial. Many testing machines test bolts by inertia, such as the testing techniques that we adopted. Most testing machines used to date are direct testing machines.

Note the path of reasoning that led to the testing (Figure 19). It started at the top line with 60-degree lubricated threads. Then it selected the model of the cantilever as it was a critical cause of failure of bolts under vibration. Then follow the figure down to "TESTED" which included both sine and random testing. The results of the tests will be discussed later. Note that from the tested model the direct testing or simple static tests could be studied by direct inference. Also note that other models can follow the type of testing given the cantilever, including "double shear" and "shear bending".

BOLT VIBRATION TESTS ON A CANTILEVER BEAM

We have begun our testing program with the cantilever, the simplest form of structure and the easiest to analyze, whether mathematically or with logical dialectical analysis. The following figures provide photographs of bolt vibration tests on the cantilever beam. (See the Appendix for the Test Log Book.) After we have obtained the cantilever results, we can apply those principles to more complex structures, including those which are bent.

Figures 20 through 28 are photographs of the bolt vibration tests on the cantilever beam as follows:

- Figure 20 shows the test conductor with the cantilever beam, the control monitor, and the program monitor for the test.
- Figure 21 shows the test conductor with the cantilever beam mounted on the testing machine. It consists of two 1/16-inch steel beams, 1 inch wide and 15 inches long, held together at the base with one 1/4-inch/20 bolt and nut. The bolt is class 3 and the nut is class 2. An accelerometer is mounted close to the bolt to monitor the load on the bolt. Both the load input in the machine and the load output at the bolt are measured.
- In Figure 22, the vibration technician is lubricating the threads of the bolt and under the head to keep the coefficient of friction down to approximately 0.08.
- In Figure 23 the bolt is torqued.

Figure 20. 1-G sine sweep.

Figure 21. Overall testing.

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Figure 22. Bolt lubrication.

Figure 23. Bolt torquing.

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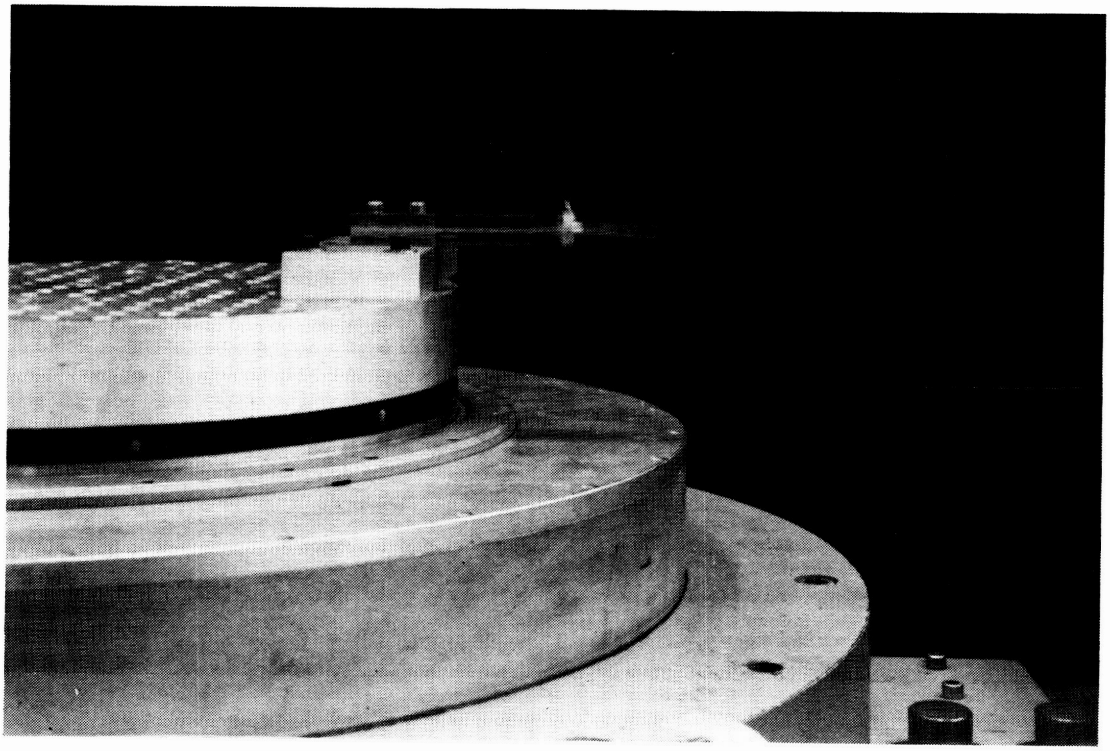

Figure 24. 1-G sine sweep.

Figure 25. Amplitude at 24.7 Hz.

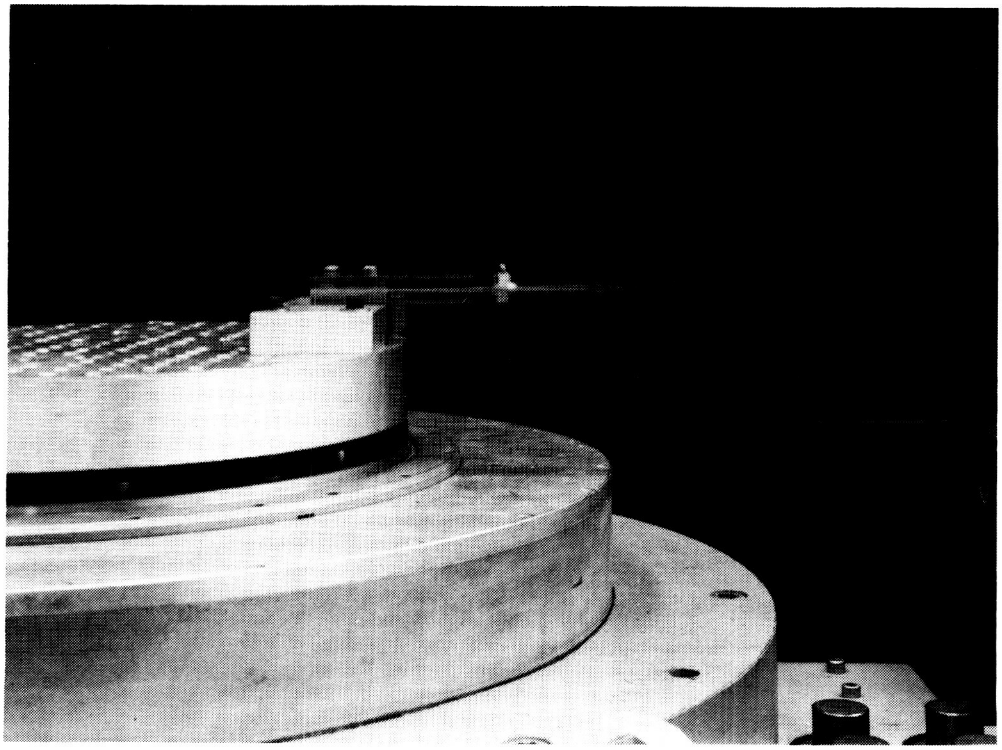

Figure 26. 20 to 2000 Hz at 5 G_{rms}.

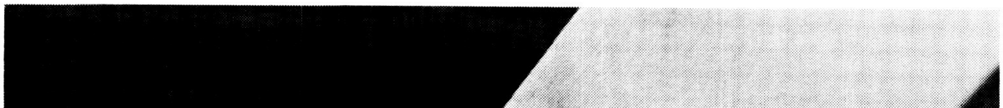

Figure 27. Neutral position (no shear).

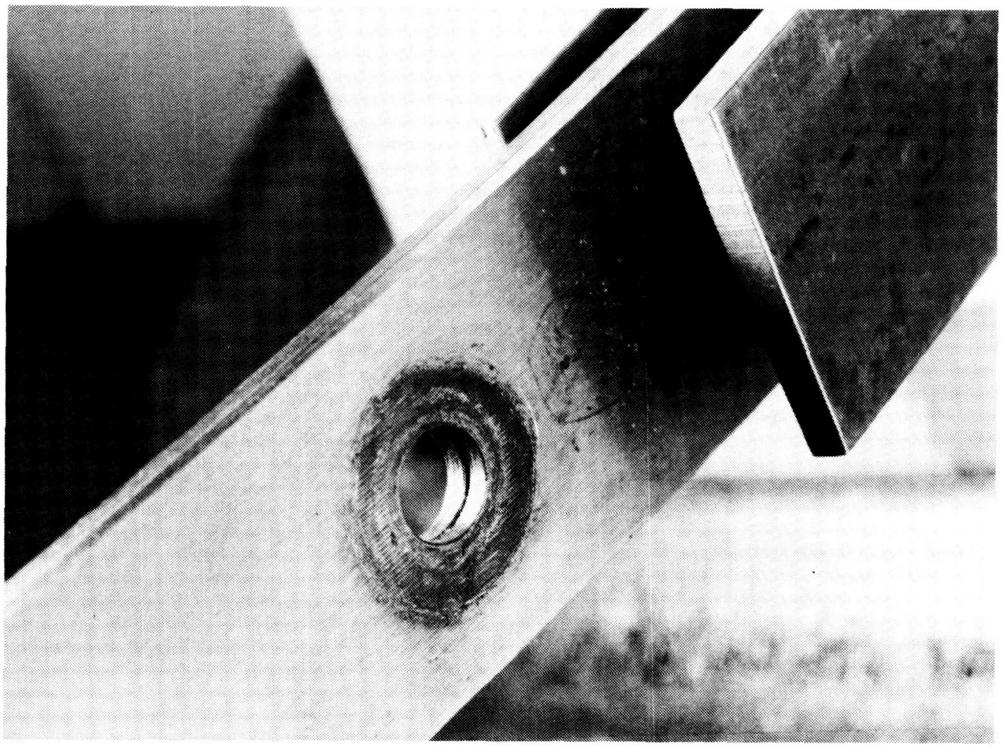

Figure 28. Bent down (full shear).

- In Figure 24, the beam is vibrating with 1-G sine sweep to determine the vibration spectrum response–from 20 to 2000 Hz.

- In Figure 25, the amplitude of vibration at the first fundamental frequency is illustrated–24.7 Hz. The input is 2 G, and the output at the bolt is approximately 10 G.

- Figure 26 shows random vibration (5 G_{rms}) from 20 to 2000 Hz.

- Figure 27 shows two beams in the neutral position with the bolt removed. Notice that the top hole is directly above the bottom hole because no shear load is present.

- Figure 28 shows the beam bent slightly down, while a shearing motion is recorded in the picture. Note that the edge of the top beam is away from the hole in the bottom beam. The bolt prevents this gap from appearing and thus induces shearing loads on the bolt.

The input to the testing machine measured on the head of the machine holding the bolt fixture is measured and recorded on graphs (Figures 29 through 40). The output at the bolt is also measured and graphed.

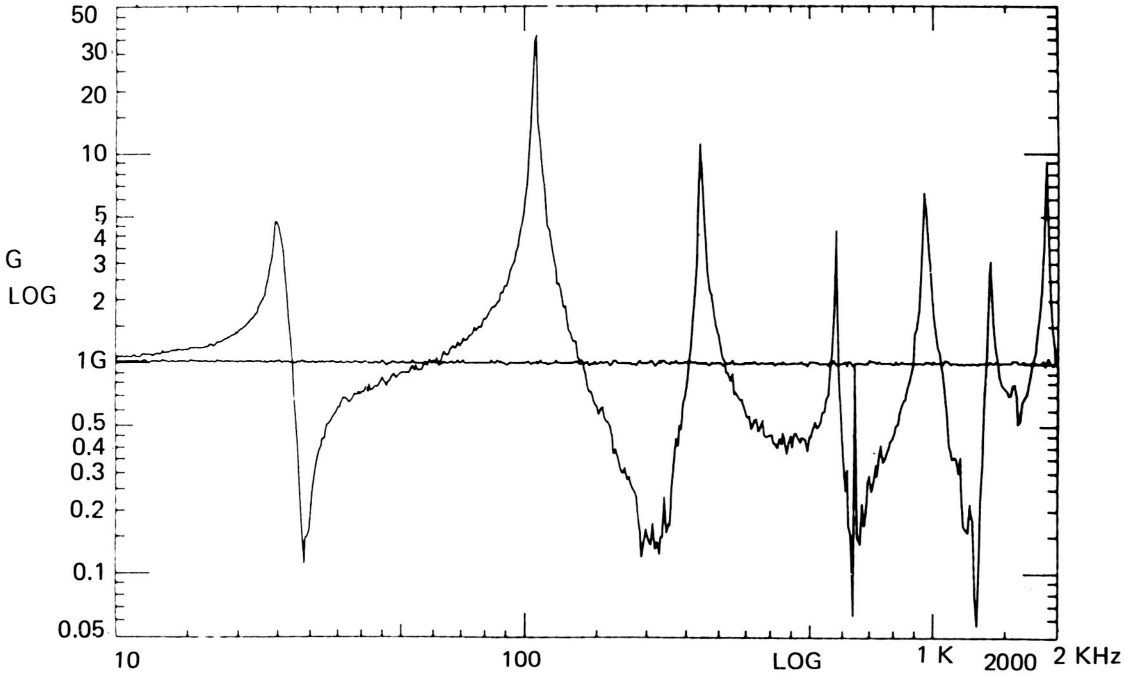

Figure 29. Sine sweep (1 G at 20 Hz to 2 kHz.

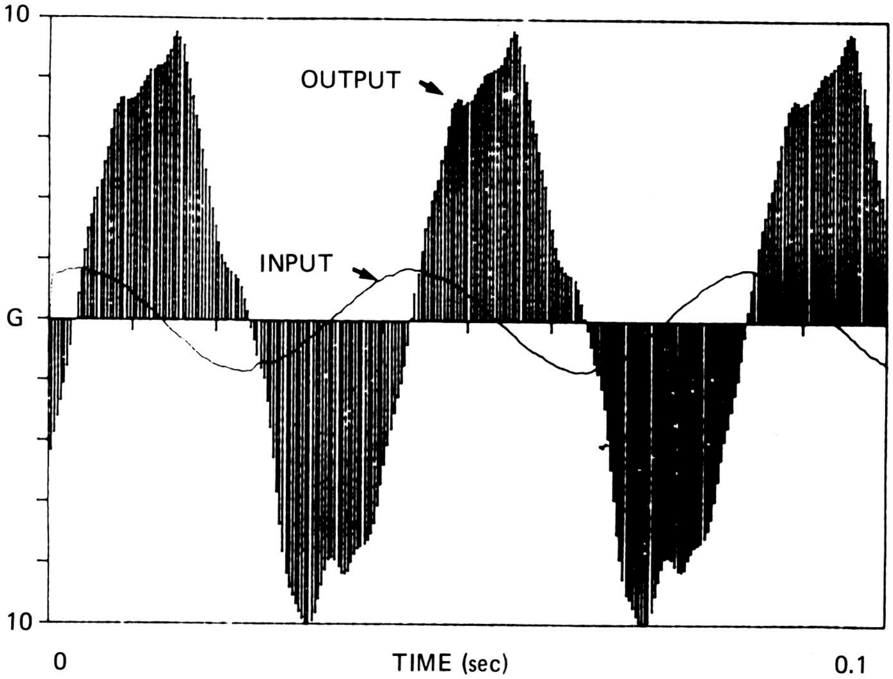

Figure 30. Sine dwell (2 G at 24.7 Hz).

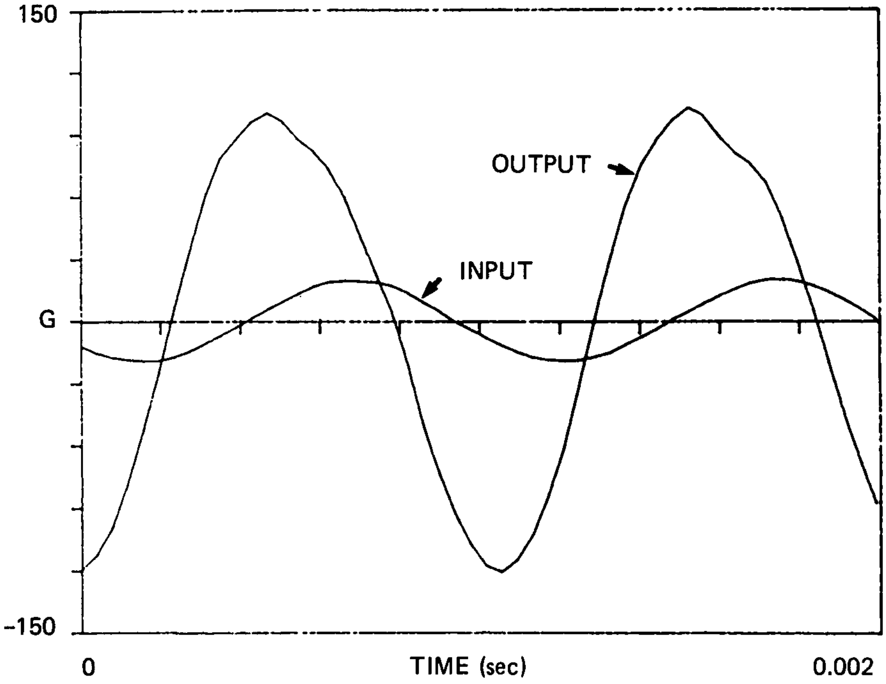

Figure 31. Sine test (20 G at 947 Hz).

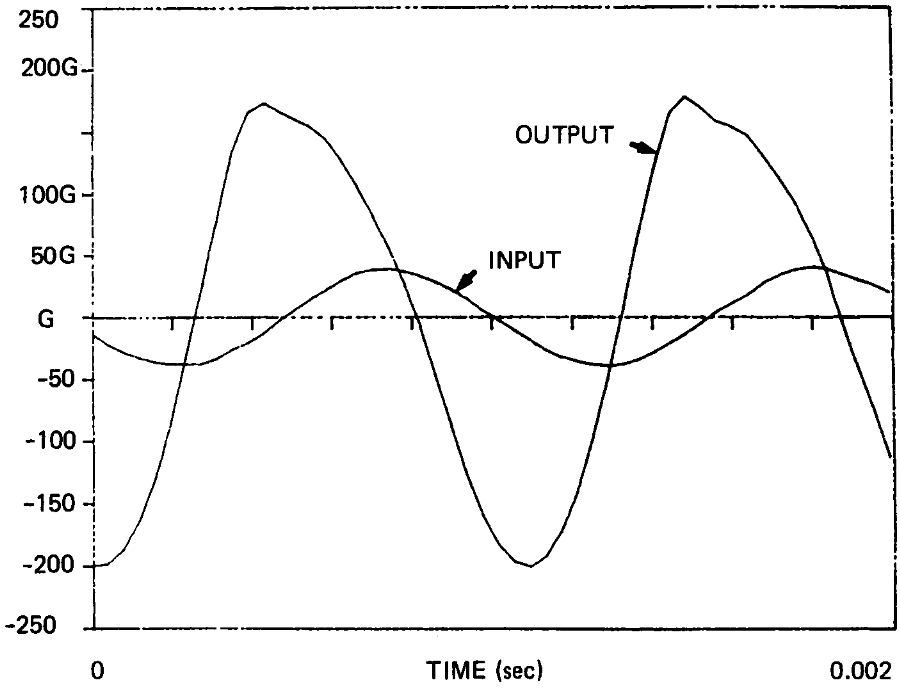

Figure 32. 40-G sine at 941 Hz.

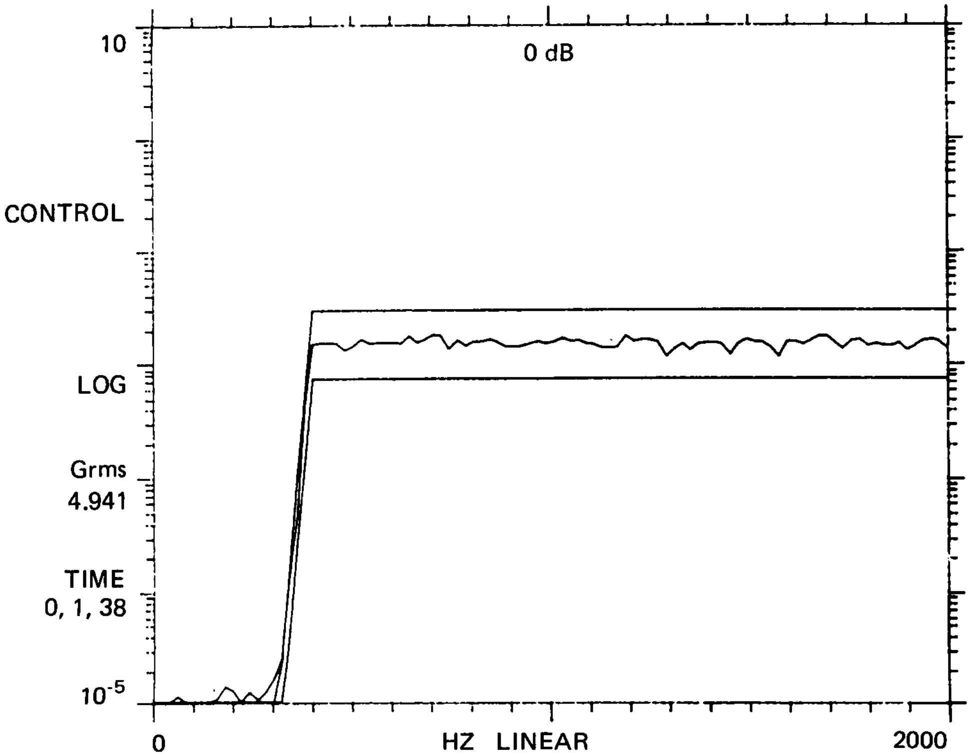

Figure 33. Input 20 to 2000 Hz at 1 G.

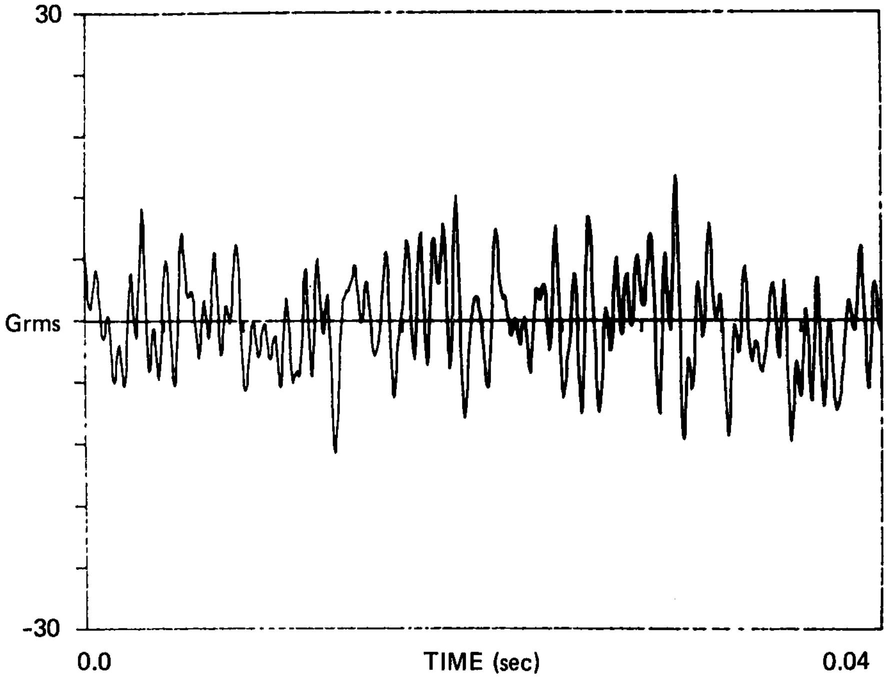

Figure 34. Input 20 to 2000 Hz at 5 G_{rms}.

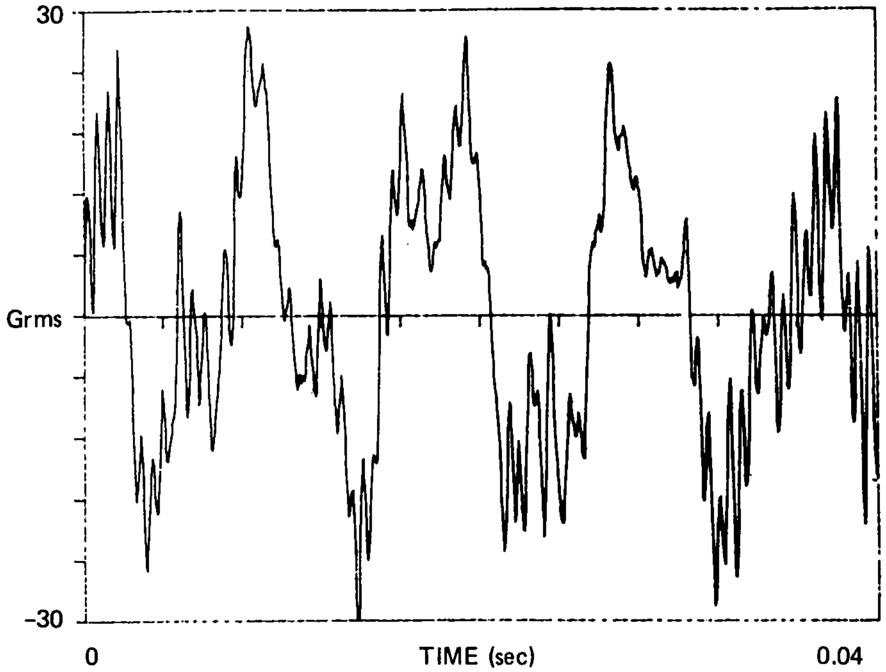

Figure 35. Output 20 to 2000 Hz at 5 G_{rms}.

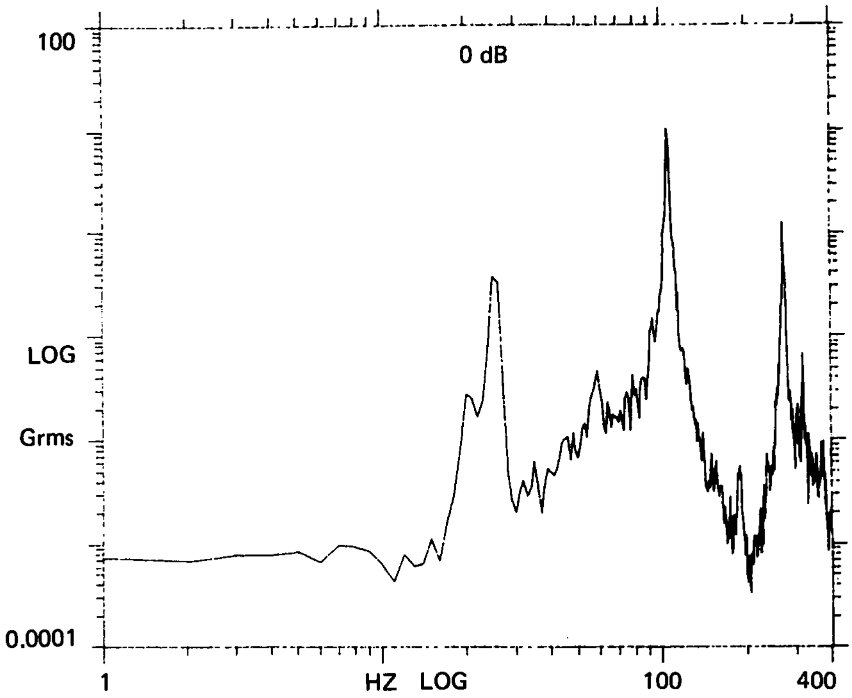

Figure 36. Output 20 to 400 Hz at 2 G_{rms}.

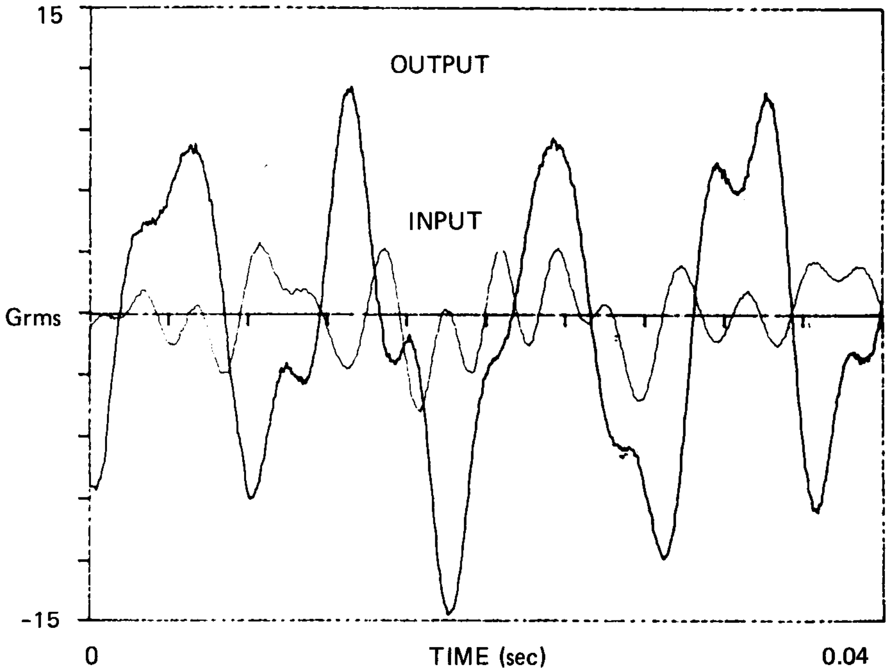

Figure 37. Input/output 20 to 400 Hz at 2 G_{rms}.

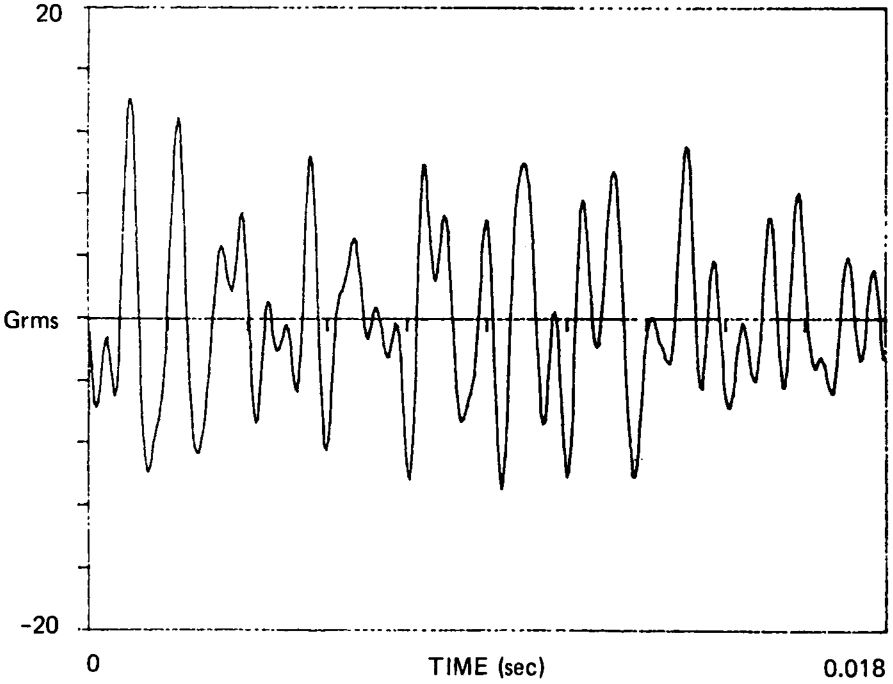

Figure 38. Input 400 to 2000 Hz at 5 G_{rms}.

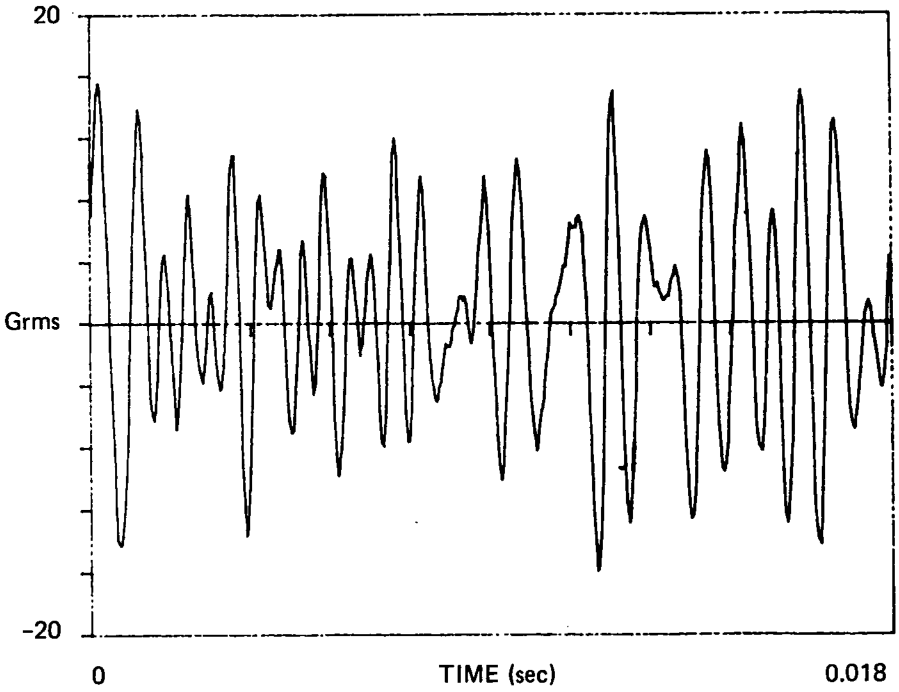

Figure 39. Output 400 to 2000 Hz at 5 G_{rms}.

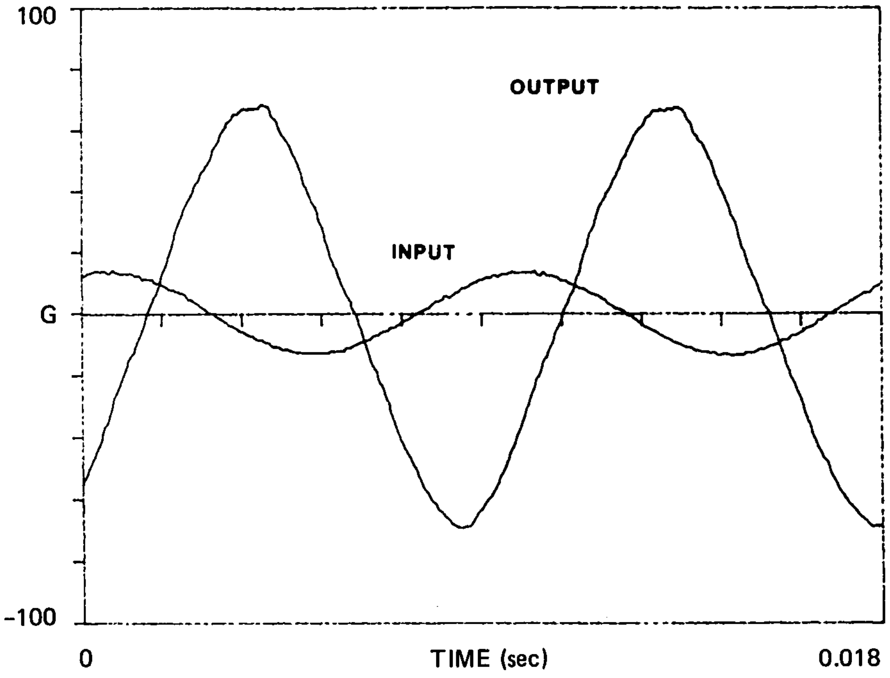

Figure 40. Input/output 107 Hz at 5 G.

We can better understand the full meaning of these graphs by simultaneously going over the individual tests as written in the following section, "Individual Tests." These are:

- Figure 29: Sine Sweep–Figure 29 is a response spectrum from 20 to 2000 Hz with a 1-G input. The points studied were the fundamental at 24.7 Hz, the second harmonic at 107 Hz, and the fifth harmonic at 941 Hz. The response of the second harmonic is double that of the fundamental. As far as this study is concerned, where both G and amplitude are concerned, even though the G load is higher at 107 Hz, the amplitude is smaller. For example, 30 G at 24.7 Hz is 0.9 inch, and 30 G at 107 Hz is 0.05 inch.

- Figure 30: Sine Dwell–The input at the base of the cantilever is subject to 2 G, whereas the output at the bolt is approximately 10 G. The input is a pure sine curve, and the output is an approximate sine curve. It has a little of the second harmonic in it, because the second harmonic is more pronounced than the fundamental. (See Figure 29.)

- Figure 31: 20 G at 947 Hz–This is a sine test of the fifth harmonic. The input is approximately 20 G, whereas the output is 120 G. In this test, the next harmonic is not as pronounced. The output curve is rather clean.

- Figure 32: 40-G Sine at 941 Hz–This figure is a repeat of Figure 31, except that the input has been raised to 40 G. The output was approximately 200 G.

- Figure 33: Input 20 to 2000 Hz at 1 G–The input begins at approximately 20 Hz. Because it is random, it does not come in all at once. The random signal is slightly up and down all the way to 2000 Hz. The upper and lower limit drawn on the curve is ±3 dB.

- Figure 34: Input 20 to 2000 Hz at 5-G_{rms}–Over a period of 0.04 second, the exact output on the top of the machine is shown. This output demonstrates clearly that random vibration is a series of many frequencies and many amplitudes.

- Figure 35: Output 20 to 2000 Hz at 5 G_{rms}–Whereas the input is shown on Figure 34 as a series of frequencies at different amplitudes, the output indicates that the beam responds *only* with large motions at the fundamental and the harmonics of the cantilever. The fundamental and the second and third harmonics are clearly shown as coming through and resonating.

- Figure 36: Output 20 to 400 Hz at 2 G_{rms}–In this graph, the random vibration is cut down to 20 to 400 Hz rather than from 20 to 2000 Hz. All of the energy is concentrated in this frequency range. Clearly shown are the fundamental of 24.7 Hz, the second harmonic of 107 Hz, and the minor upper harmonics. The minor higher harmonics can be caused because they are generally excited in the higher range with low-frequency resonance.

- Figure 37: Input/Output 20 to 400 Hz at 2 G_{rms}–The input and the output curves are shown for the random load of 20 to 400 Hz. The fundamental and second harmonic are clearly coming through. The input consists of many frequencies from 20 to 400 Hz.

- Figure 38: Input 400 to 2000 Hz at 5 G_{rms}–Note that the time duration is not 0.04 second but 0.018 second. The input consists of many frequencies and many amplitudes from 400 to 2000 Hz.

- Figure 39: Output 400 to 2000 Hz at 5 G_{rms}–The prominent output frequencies are the harmonics of the cantilever in the 400 to 2000 Hz range.

- Figure 40: Input/output 107 Hz at 5 G–This graph shows the second harmonic. The input is 5 G, but the output is approximately 70 G. This is the prominent response of the cantilever. Not only was this evident from previous graphs, but it is useful to note that the output curve is a good sine curve that indicates an almost clean response without the interference of other frequencies.

Individual Tests

This section summarizes the results of the individual bolt vibration tests. A summary of results and implications of the findings follows.

Test 1

This test was a 1-G sine sweep from 20 to 2000 Hz to find the fundamental and harmonics of the cantilever. See Figure 29.

Test 2

A sine dwell of 2 G was held at the fundamental 24.7 Hz. Input to the table was 0.065 inch, the magnification at the bolt was 0.65 inch, and the motion at the tip was 2.1 inches. The time required for the bolt to back off was measured in seconds by noting the change in frequency and power to the amplifier. The time for complete backoff, measured by the test technician, was 24.7 seconds. See Figures 25 and 30.

Test 3

This test was performed at 25.9 Hz to demonstrate that a bolt vibrates off only at its fundamental frequency where the amplitude is highest. Even a slight shift in frequency will cause it to drop out of resonance; if the shear load on the bolt is lowered, the bolt does not back off. There was no substantial response and there was no backing off of the bolt.

Test 4

This test, shown in Figure 32, was a sine dwell at 947 Hz, one of the higher harmonics found in test 1. The input was 20 G and the output was 120 G. There was no backoff of the bolt. This load is very high (120 G), and if the bolt could back off at any time in this frequency range, it would most likely do so under this condition. This test amounts to 120 G (a resonant condition) for 284,000 reversals with no backing off of the bolt. The amplitude of the input was 0.0005 inch, and the amplitude of the output was 0.0025 inch.

Test 5

This test (Figure 32) was performed at 941 Hz with an input of 40 G and an output of 200 G. This test was equivalent to 284,000 reversals of load at 40-G input with no backing off of the bolt.

Test 6

This is a random vibration test (Figure 33) of 1 G_{rms} from 20 to 2000 Hz.

Test 7

This test is a random vibration test (Figure 26) of 5 G_{rms} from 20 to 2000 Hz. The input is plotted in Figure 34, and the output is plotted in Figure 35. There was no backing off of the bolt.

Test 8

This is a random vibration test (Figure 26) of 10 G_{rms} from 20 to 2000 Hz. The input is shown by Figure 34, and the output is shown by Figure 35. Note from Figure 26 that the amplitude was quite low in inches, whereas the G values get larger, but not as much as the G values in the sine vibration tests. There was no backing off of the bolt.

Test 9

This is a random vibration test of 20-G_{rms} input from 20 to 2000 Hz. The output at the bolt was higher. Note that the random input consists of many different frequencies from 20 to 2000 Hz, but the output consists of only a few discreet outputs, with the fundamental and harmonics as found in test 1. The bolt backed off completely in 2.75 minutes. Because this was not a sine test, it was impossible to see the change in resonance. This backing off could be caused by the large amplitude of the low frequency inputs when the overall energy reached 20 G_{rms}.

Test 10

This test is a similar 20- to 2000-Hz random vibration test with a magnitude of 15 G_{rms} input. The bolt did not back off in 5 minutes.

Test 11

This test is a low-frequency random vibration test shaped to give 2 G_{rms} from 20 to 400 Hz. In sine testing, the bolt backed off at low frequency only. To determine if the bolt would back off with random vibration as well, a shaped random was performed to pick up the fundamental of 24.7 Hz and the second harmonic of 107 Hz. The input is a typical low-frequency random as illustrated in Figure 37, and the output is shown in Figure 36. In Figure 37, note that the two prominent frequencies of 24.7 and 107 clearly came through.

Test 12

This test was conducted for the same reason as test 11: to show input.

Test 13

This test is the same low-frequency random vibration test with the G level raised to 5 G_{rms}. The bolt did not back off.

Test 14

This test is similar to tests 11 and 13, with an input of 10 G_{rms}. The bolt backed all the way off in 2 minutes.

Test 15

This is a random vibration test performed at 1000 to 2000 Hz to simulate the high-frequency spectrum. The input is shown in Figure 38, and the output is shown in Figure 39. The input was 5 G_{rms}. The bolt did not back off.

Test 16

This test is the same as test 15 from 1000 Hz to 2000 Hz, but the input was raised to 20 G_{rms}. The input is shown in Figure 38, and the output is shown in Figure 39. This test demonstrates the same effect as that of the sine testing in the input. (The input in sine and random are both high frequency.) The bolt did not vibrate off in random. Thus, both sine and random illustrated that low frequency backed off bolts, but high frequency did not cause bolts to back off.

Test 17

The remaining question is what happens when low frequency and high frequency are used together. Does the threshold of low frequency change, causing bolts to back off? Can high frequency change the wave pattern of loads on the bolt and cause it to back off sooner? In this test, 15 G_{rms} was introduced to the input with a shaped random of 20 to 400 Hz and combined with 1000 to 2000 Hz. Care was used to mathematically study the energy input to ensure that the same energy load was applied to the low frequency alone and with the high frequency combined. The bolt backed off in 2 minutes and 21 seconds. This result will be compared later with low-frequency random alone.

Test 18

The same input of 20 to 400 Hz, along with 1000 to 2000 Hz, was applied to the input at 10 G_{rms}. The bolt did not back off in 10 minutes. In the previous test of 10 G_{rms} random along with 20 to 400 Hz only, the bolt backed off in 2 minutes. Observations of the tests indicated that the high-frequency random caused the "Q," or magnification factor, of the low frequency to drop slightly when the higher random was added. Note that 15 G_{rms} overall from 20 to 400 and 1000 to 2000 Hz causes a random input of 10 G_{rms} at 20 to 400 Hz. Thus, 15 G_{rms} overall is the same as 10 G_{rms} between 20 and 400 Hz.

Test 19

This test was performed to measure the amplitude of vibration at the fundamental. The input was 0.016 inch, the output at the bolt was 0.48 inch, and the output at the tip of the cantilever was 1.0 inch.

Test 20

This test is the same as test 19, except that the amplitude was changed to 1 G. The input was 0.03 inch, the output at the bolt was 0.6 inch, and the output at the end was 1.6 inch.

Test 21

This test is the same as test 19 with an input amplitude of 1.5 G and 0.045 inch. The output at the bolt was 0.625 inch, and the output at the end was 2.0 inches.

Test 22

This test is the same as test 19 with the input amplitude of 2 G and 0.06 inch. The output at the bolt was 0.65 inch, and the output at the tip was 2.1 inches. Obviously, resonance "Q" values were not proportional; they are not expected to be because the velocity is the integration of the acceleration with respect to time, and the displacement is in the integration of the velocity with respect to time. Furthermore, with large amplitudes, any slight change in linearity of motion will cause a change in the phase response that will bring the resonance down.

Tests 23 through 34

In these tests, the second harmonic was 107 Hz. The fundamental had the largest amplitude, but the second harmonic had the next largest amplitude. These tests were performed to determine if an abnormally large amplitude for 107 Hz would cause a bolt to back off. With 50-G input, the output at the bolt was approximately 230 G. (The accelerometer popped off the beam.) The amplitude of 230 G at 107 Hz was a little over 0.2 inch. The nut came off in 10 seconds. These tests did not consistently cause the bolts to back off.

In one test at 14-G input, the bolts backed off. Later, with 17 G, they did not back off. These loads are very high (well above anything considered to be standard) and higher than those loads expected in over 99 percent of field use. The tests were performed to demonstrate that even with a second harmonic (which normally vibrates at a much lower amplitude in inches or displacement), if the *amplitude* is allowed to get high enough, the bolt will probably back off whether it is the fundamental or second or third harmonic.

The key issue is amplitude. This test supports the theory of some engineers that it is not the waveform or frequency, but the amplitude, that causes bolts to back off in vibration.

Tests 35 through 37

These tests were performed to verify the previous data. The amplitudes were 10, 14, and 20 G_{rms}, with random frequencies of 20 to 400 Hz, and 1000 to 2000 Hz.

Tests 38 through 40

These tests repeated the random tests of 20 to 400 Hz. The 10-G_{rms} time for backoff was previously 2 minutes. In this test, it was 2 minutes and 22 seconds, which is well within the accuracy of the measurements for this type of test.

Tests 41 through 47

These tests were dual sine tests in which input frequencies of 944 and 24.7 Hz were applied simultaneously. To date, testing on sine inputs has indicated that low-frequency (which is primarily amplitude-sensitive) vibration caused bolts to back off. High frequency and low amplitude did not. The result of adding high frequency to the low frequency was determined. With 2 G alone, the bolt backed off in 24 seconds. With the combination, the bolt backed off in 1 minute and 27 seconds. This result follows the same trend noted in the random testing. Observation of the test demonstrated that the presence of the high frequency on top of the low frequency tended to dephase the low frequency and change its waveform and overall displacement amplitude. Design engineers know that dephasing a bad resonant condition will lower the natural frequency and the amplitude. It is common to see this done in many structural dynamic designs.

Test Fixture

The model for testing (Figure 41) was designed by Haviland (reference 4).

Summary of Tests

The goal of these tests was to select the proper cantilever beam of Figures 12 and 41 and subject it to loads of sine and random vibration similar to the waveforms of Figures 3 and 4. Many different variations of these waveforms were used, and observations were made to see if the nut was vibrating off the bolt. Alternate methods of testing can be used. For example, we could quickly twist the nut by hand. Or, for more accurate results, we could observe the testing machine to determine the change in natural frequency.

Figure 19 summarizes retroduction as applied to bolts and nuts. We must study this figure carefully to determine the extent of the tests and the accuracy we desire; then we should return to the retroductive model in Figure 18, and seek a rational approach to future study.

From Figure 19, we can make the following observations:

1. More than 20 billion bolts are used in the United States; most are made to American Standards, which include such classes as SAE, NASA, MIL, and AN bolts.

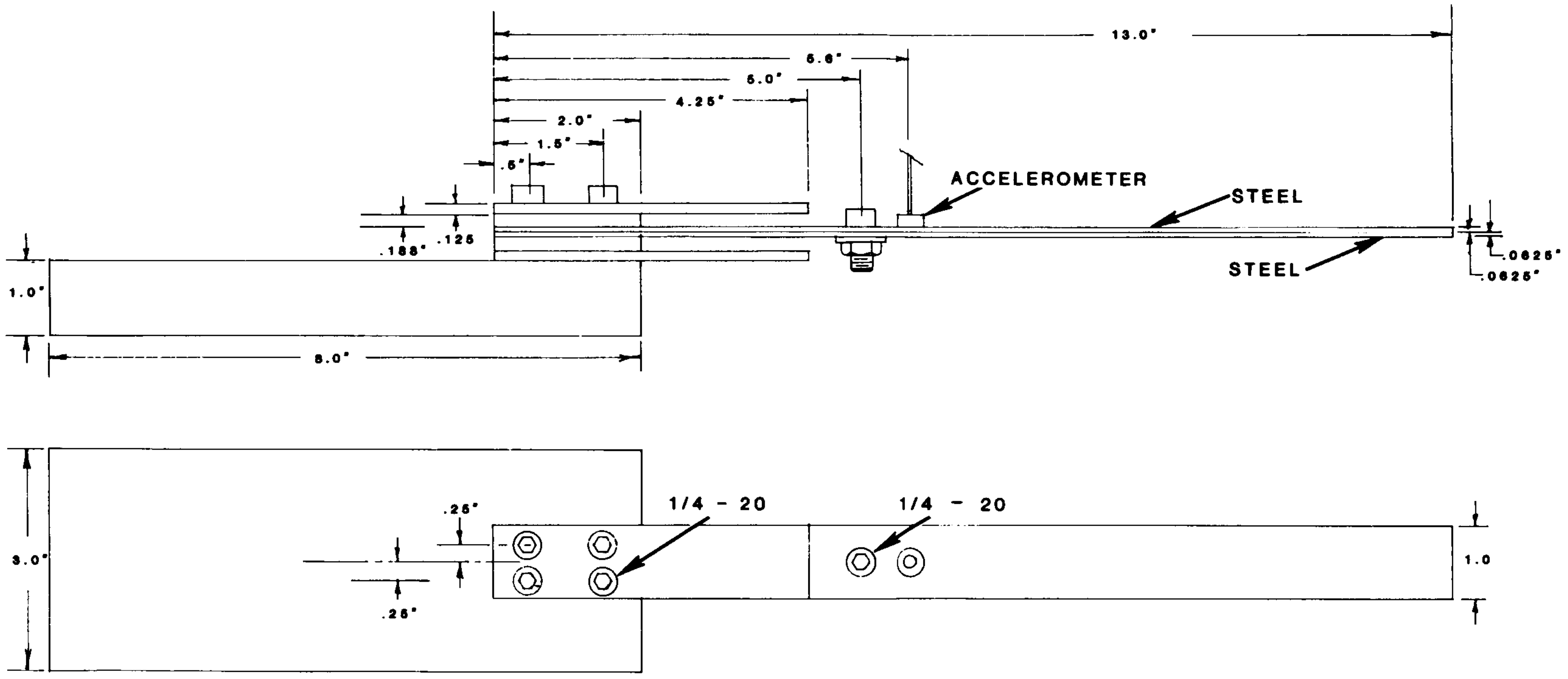

Figure 41. Test fixture for giving horizontal shear to bolts.

2. Most bolts that are undergoing vibration loads are mounted as shown in Figures 6, 7, 8, 9, 12, and 13, if horizontal shear is the first concern.
3. All six of these loading conditions can be divided into either direct loading or inertial loading.
4. Inertial loading, as described in Figure 12, was used for testing. There is a load of horizontal shear on the bolt caused by bending. (Most of the uses of bolts in the government and industry are vibrated under inertial conditions.)
5. These beam tests were sine and random testing. Specifically, the tests were sine sweep, sine dwell, and sine dwell, with two frequencies applied simultaneously. The random-load tests used broadband random and shaped random to include low-frequency random, high frequency random, and then a combination of low-frequency random with high-frequency random.
6. The only tests not performed were shock loads. For most cases, including the cantilever tested, the shock loads would be mitigated by the time they reached the bolt, and they would be reduced to a form of transient vibration. This type of loading has already been included in the sine and random testing program. Direct shock loads can be applied at a later date.
7. The nut backed off the bolt with low frequency vibration or when the *amplitude of bending was relatively high*. This phenomenon was observed during sine inputs of tests No. 2, 25, 27, 28, 29, 44, 45, 46, and 47. Further, this phenomenon was observed during random vibration tests No. 9, 14, 17, 36, 37, 39, and 40. These are all low frequency. The nut did not back off during sine inputs of tests No. 4, 5, 30, 31, 32, 33, 34, 41, 42, 43, and 45. Further, this phenomenon was observed during random vibration tests No. 15, 16, and 35. These are all high frequency low amplitude tests. With this phenomenon it is well known that the lower frequency tests have high amplitude and that the higher frequency tests have low amplitudes. It was observed that shear loads cause bolts to back off because shear was the only substantial load applied during all of the tests.
8. The tests were consistent with both sine and random testing. Many of the tests were duplicated by a completely different test conductor when the original test conductor was not in the test area.

CONTINUED ANALYSIS AND SYNTHESIS

A return to Figure 18 demonstrates that the testing just completed is a partial solution to the thing sought; how and why bolts and nuts separate during vibration. The next step is to follow the same path from the upper right down to "Types of vibration loads." In the synthesis of this analysis we can test either inertial or direct loading. Inertial loading was performed and records were evaluated. Instead of continuing with the dialectic retroductive process, we should work with the mathematical deduction illustrated in Figures 1 and 2. Carefully marking the deflected structure during vibration (Figure 22) and equating it to F = ma, we can calculate the shear and bending moments mathematically. (See Figures 42 and 43.) Then, assuming that the shearing force is causing the bolts to back off, we can calculate the static load of Figure 42 to give the same shearing force at the bolt in Figure 43. After we perform the analysis, we can use the testing to check the analysis, following

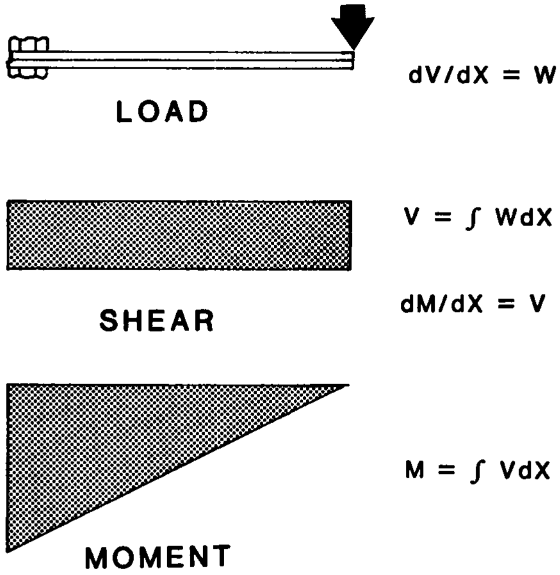

Figure 42. Shear and bending moment of direct loading.

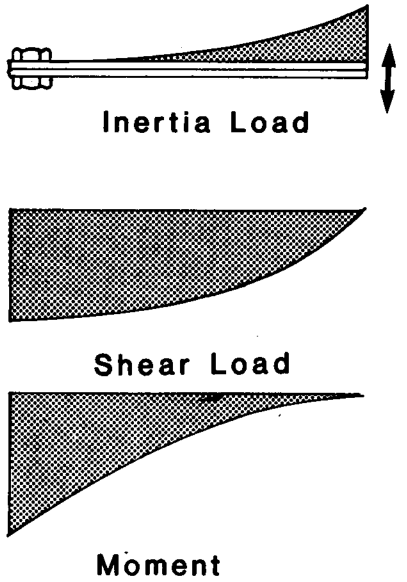

Figure 43. Shear and bending moment of inertial loading.

the mathematical deduction of Figures 1 and 2. (The mathematical analytical solution is faster than further retroduction.) Next, let us return to the retroductive model of Figure 18 and slide down the analytical scale to ". . .(2) What are the forms of the structure. . . ." We will combine this abstraction with the previous mathematical deduction of the cantilever to see if other forms of structures can be analyzed on the basis of the original tests. Figure 44 is a typical bent, which is the next structural form above a cantilever. It is analyzed with a single load in the center. The deflected structure is drawn while the bent is vibrating. Figure 45 illustrates the reactive forces, Figure 46 is the moment diagram, and Figure 47 is the shear diagram for the bent. Figure 48 shows the same bent made up of three members held together by bolts. Figure 47 shows the shearing load on the bolt, which could cause it to back off. Thus, a direct mathematical relationship exists between the bent and the cantilever. The tests on the cantilever apply to the bent. This method of retroduction leads to more complex structures. Computer analysis of very complex structures can find shearing forces that could be applied to this system. The advantage of the retroductive model of Figure 18 is that it offers a quick sweeping look through the entire analysis and synthesis to find possible mathematical deductions with either one or several points at one time.

Using the retroductive model of Figure 18, we see that another structural analysis is used in the vibration of plates. In government and industry, many plates are held in with bolts, and in many cases, plate vibration causes the bolts to back off, particularly in plates that are put on and taken off many times. Figure 49 shows how a plate can be analyzed as a beam (reference 6). Bolts mounted on the plate can be analyzed as the cantilever beam or the bent. Figure 50 shows a plate with restraints on all four sides, which can be analyzed as two beams (reference 6).

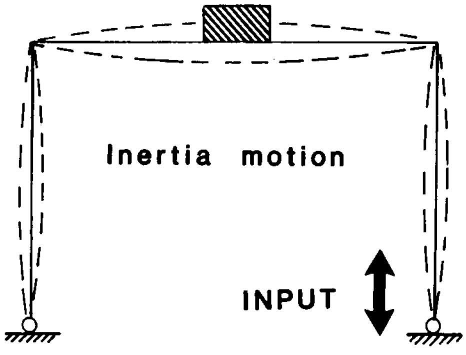

Figure 44. Bent input.

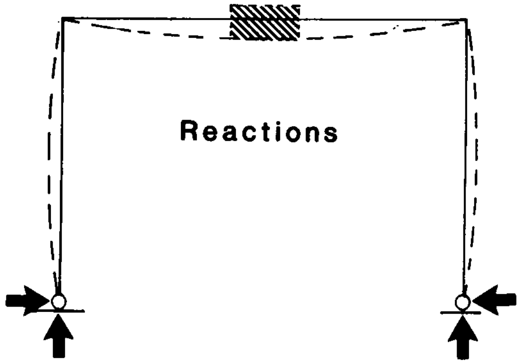

Figure 45. Deflection of bent.

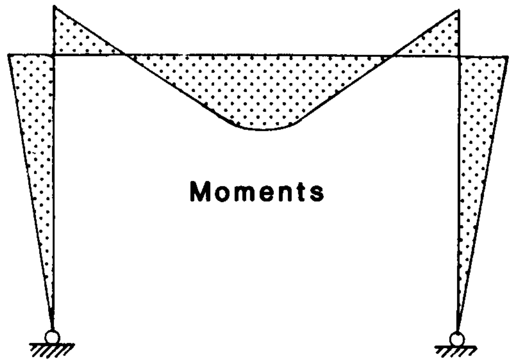

Figure 46. Bending moment (bent).

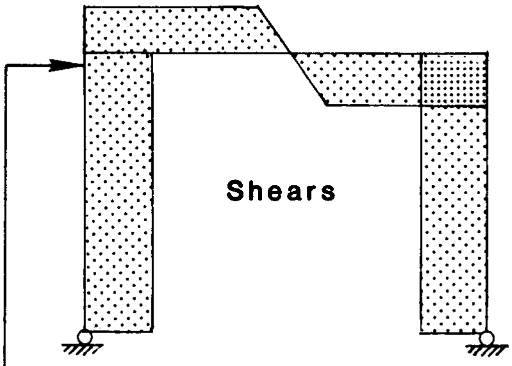

Figure 47. Shear curves (bent).

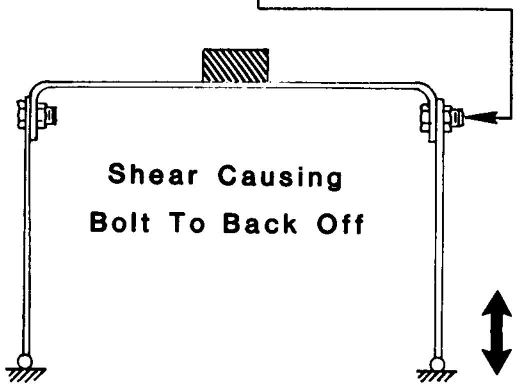

Figure 48. Shear applied to bolt on bent.

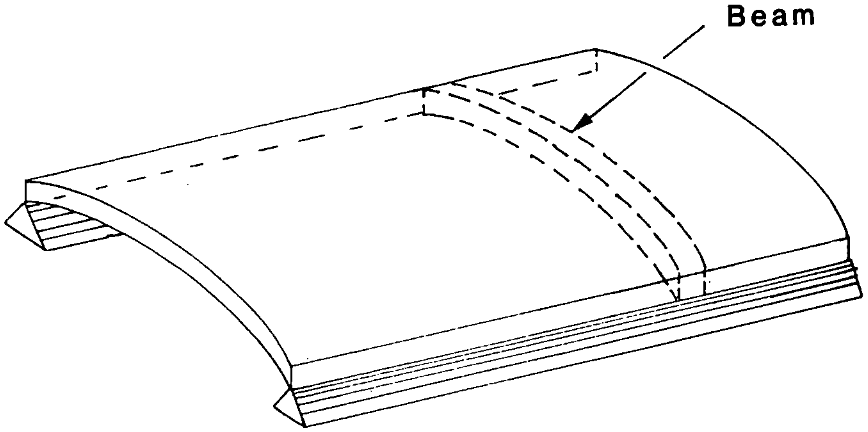

Figure 49. Vibrating plate held at two edges.

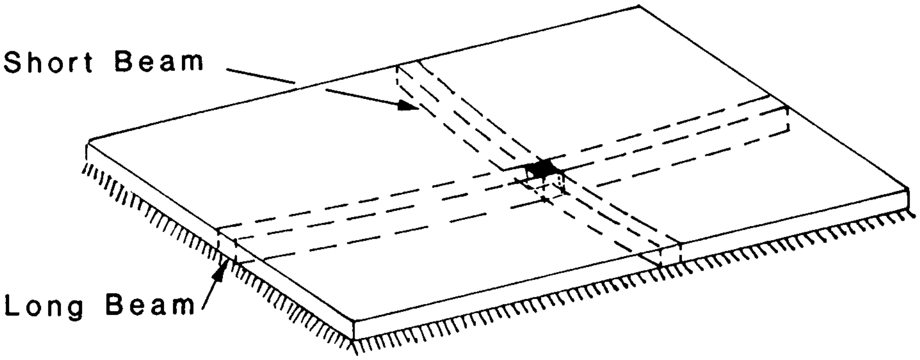

Figure 50. Vibrating plate held at four edges.

SUMMARY OF RETRODUCTIVE STUDY

A new method of scientific research, called retroduction, is introduced. A design problem is developed to explain the terms and methods of the study:

1. The beam requirements are given (listed as *Given*).
2. The experience of the designer and a list of mathematical equations for solving this problem are stated (listed as *Known*).
3. Every point that could come up in the design, including the solutions to individual phases of the problem, is listed in the form of a dialectic question.
4. The universal or overall answers to the individual questions are listed.
5. The nonconsequential questions are eliminated.
6. The remaining questions are listed in the order that they must be answered to continue the study.
7. The order is now such that the list of dialectic questions form the analysis, and the answers to the questions form the synthesis.
8. The last question of the analysis is the first answer in the synthesis.
9. The answers to the questions form the thing sought:
    a. The abstract beam that can now be solved with the mathematical questions known.
    b. The ball-park beam used by designers to finalize the design. (See Figure 17.)

The research into why and how nuts back off bolts is studied in the same way:

1. The *Known* elements are not mathematical equations, but principles to be followed in the study. These come from past experience.
2. The *Given* items are the directions of the research committee.
3. The thing sought is: When does the nut back off the bolt during vibration?
4. The dialectic questions about everything that is associated with the vibration of bolts are listed.
5. The individual questions are answered.

6. The questions that could be eliminated at the beginning of the study are taken from the list temporarily.

7. The remaining list, including the *Given* and *Known* items, is provided. These questions are studied to see which should be answered first, second, etc. to complete the first phase of the study.

8. The dialectic questions are shown in Figure 19 as one order of dialectic questions that would come to an absolute conclusion about a phase of the study.

Tests performed to check the retroductive study demonstrated that low frequency, not high frequency, caused nuts to back off during sine and random vibration on a cantilever. Next, we made a mathematical model of a static test to verify the results of the dynamic tests and used the mathematical analysis to verify the dialectic study and dialectic testing.

Bents are studied with mathematical analytical techniques to demonstrate that all structures do not have to be tested to get universal results. The bents can now be tested to verify the calculations.

DEFINITION OF TERMS

Abstraction	– the process of determining the essential characteristics from the dialectic questions answered, considering the *Given* and *Known* and giving the proper order to these characteristics
Analysis	– the process of resolving the whole into the parts
Ball-park answer	– see Final cause
Dialectics	– a logical or rational method of analyzing
Dialectic logical analysis	– a logical or rational method of analysis; the art of examining opinions or ideas logically, often by the method of questions and answers
Efficient cause	– the dialectic questions must show who designed the object, who made it, and who assembled the parts. The efficient cause could also be a machine or any element of nature that acts as an agent to bring about the final cause; the efficient cause always leads to the final cause.
Final cause	– the ball-park answer; the goal that is always sought. The result of dialectic reasoning in logical analysis is a ball-park answer arrived at through abstraction of the dialectic answers.
Formal cause	– must answer all of the questions with respect to the way the object is made to attain the final cause. For example, a chair is made in its particular form so that we may sit in it. Although we may also stand on it, this possibility does not take away from the fact that it was made to be sat in. The secondary use is unimportant.
Given and *Known*	– In retroduction, *Given* and *Known* items are applied to design, invention, and research. *Given* elements are brought to the designer in the form of specific numbers and to the engineer in the form of guidelines and goals. *Known* elements are brought to the designer in the form of physical data and to the engineer in the form of principles of study.
Material cause	– leads directly to the final cause; in putting together the dialectic questions, we must consider material to be used.

Mathematical analysis – the process of assigning numbers to the element to be analyzed and its components. For example, in a beam the bending stress (S) is analyzed by assigning numbers to the elements that comprise it ($S = mc/I$), where S is the element to be analyzed, m is the moment, c is the distance from the neutral axis to the outside, and I is the second moment of inertia of the cross section under investigation. If m is 10,000 inch-pounds, c is 4 inches, and I is 20 inches (reference 5), the stress $S = 10{,}000 \times 4/20 = 2000$ psi.

Principle – that from which everything else follows in any way. For example, a principle of house construction (though possibly not a rule or law) is that anything used in building the house should not endanger the house's occupants.

Retroduction – a process of dialectic questioning that begins first, with the thing desired; proceeds to *Given* items either in the form of dimensions or limits of research, and then to *Known* mathematical forms of analysis in design and principles of study in research. Finally, analysis and synthesis are used to abstract the dialectic questions to arrive at the thing desired.

Synthesis – the putting together of all of the answers to the dialectic questions by means of of abstraction to arrive at the final cause. During this process, new questions may arise that may have to be answered. The *Given* and *Known* items must be considered during each step to arrive at the final cause.

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APPENDIX

TEST LOG BOOK

No.	Sine or Random	Frequency or Frequency Range (Hz)	Time (change in natural frequency)	Time (bolt loose)	Photo	Input Curve	Output Curve	Deflection at Bolt (in.)	Deflection at End (in.)	Observation
1	1-G sine sweep	20-2000	1 oct min	–	1, 2, 3, 4 & 5	Flat 1-G load	Graph 1	–	–	24.7, 107, 447 Hz No bolt, 16.3 Hz
2	2-G sine	24.7	12 sec	24 sec	6	2-G flat	Graph 2	0.65	2.1	Irregular time interval because of short duration
3	2-G sine	25.9	–	–	–	–	–	–	–	No resonance, no amplitude
4	20-G sine input	947	–	–	–	Graph 3	Graph 3, 3, 120 G	–	–	–
5	40-G sine input	941	–	–	–	Graph 4	Graph 4, 200 G	–	–	–
6	Random 20-2000 1 G_{rms}	20-2000	–	–	–	Graph 5	–	–	–	–
7	Random 20-2000 5 G_{rms}	20-2000	–	–	7	Graph 6	Graph 7	–	–	–
8	Random 10-G_{rms}	20-2000	–	–	7	6	7	–	–	–
9	Random 20-G_{rms}	20-2000	–	2.75 min	7	6	7	–	–	–
10	Random 15 G_{rms}	20-2000	–	–	7	6	7	–	–	–

No.	Sine or Random	Frequency or Frequency Range (Hz)	Time (change in natural frequency)	Time (bolt loose)	Photo	Input Curve	Output Curve	Deflection at Bolt (in.)	Deflection at End (in.)	Observation
11	Random 2 G_{rms}	20-400	–	–	–	–	8	–	–	–
12	Random 2 G_{rms}	20-400	–	–	–	9	9	–	–	–
13	Random 5 G_{rms}	20-400	–	–	–	9	9	–	–	–
14	Random 10 G_{rms}	20-400	?	2 min	–	9	9	–	–	–
15	Random 5 G_{rms}	1000-2000	–	–	–	10	11	–	–	–
16	Random 20 G_{rms}	1000-2000	–	–	–	10	11	–	–	–
17	Random 15 G_{rms}	20-400 and 1000-2000	?	2 min, 21 sec	–	–	–	–	–	–
18	Random 10 G_{rms}	20-400 and 1000-2000		No back-off in 10 min	–	–	–	–	–	–
19	0.5-G sine	24.7						0.48	1.0	
20	1-G sine	24.7						0.6	1.6	
21	1.5-G sine	24.7						0.625	2.0	

No.	Sine or Random	Frequency or Frequency Range (Hz)	Time (change in natural frequency)	Time (bolt loose)	Photo	Input Curve	Output Curve	Deflection at Bolt (in.)	Deflection at End (in.)	Observation
22	2-G sine	24.7						0.65	2.1	
23	5-G sine	107	–	–						
24	10-G sine	107	–	–						
25	50-G sine	107	–	10 sec		50 G	230 G	0.23		By calculation 4.6
26	15-G sine	107	–	–		15 G 0.025	70 G	0.12		
27	20-G sine	107		10 sec						Hard to maintain
28	15-G sine	107	20 sec	27 sec						Same "Q" with higher frequency
29	12-G sine	107		30 sec						Without accelerometer
30	12-G sine	107		OK after 6 min						With accelerometer
31	12-G sine	107		No backoff after 10 min						With tape under accelerometer
32	14-G sine	107		OK after 8.5 min						
33	15-G sine	107		OK after 5 min						

No.	Sine or Random	Frequency or Frequency Range (Hz)	Time (change in natural frequency)	Time (bolt loose)	Photo	Input Curve	Output Curve	Deflection at Bolt (in.)	Deflection at End (in.)	Observation
34	17-G sine	107		OK after 5 min						Beam is hot to touch
35	Random 10 G_{rms}	20-400 and 1000-2000		OK after 5 min						5 G_{rms} in the 20-400 Hz range
36	Random 14 G_{rms}	20-400 and 1000-2000		In 5 min just started						7.5 G_{rms} in 20-400 Hz range
37	Random 20 G_{rms}	20-400 and 1000-2000		2 min, 13 sec						10 G_{rms} in 20-400 Hz range
38	Random 5 G_{rms}	20-400		—						
39	Random 7.5 G_{rms}	20-400		5 min						
40	Random 10 G_{rms}			2 min, 22 sec						
41	Dual sine	24.11 @ 1 G and 985.5 @ 10 G		No change after 5 min						
42	Dual sine	24.11 @ 2 G and 985.5 @ 10 G		No change after 4.5 min						The beam cracked
43	Dual sine	24.7 @ 1 G and 944.4 @ 10 G		No change after 4.5 min						
44	Dual sine	24.7 @ 1.5 G and 944.4 @ 10 G		5 min						Backoff torque: 5 in-lb

No.	Sine or Random	Frequency or Frequency Range (Hz)	Time (change in natural frequency)	Time (bolt loose)	Photo	Input Curve	Output Curve	Deflection at Bolt (in.)	Deflection at End (in.)	Observation
45	Dual sine	24.7 @ 2 G and 944.4 @ 10 G	34 sec	1 min, 27 sec						
46	Sine	24.7 @ 2 G	15 sec	58 sec						
47	Dual sine	24.7 @ 2 G and 944.4 @ 10 G	65 sec	2 min, 34 sec						

1. Report No.
NASA TM-4001

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
An Application of Retroduction to Analyzing and Testing the Backing Off of Nuts and Bolts During Dynamic Loading

5. Report Date
June 1987

6. Performing Organization Code
750

7. Author(s)
James J. Kerley

8. Performing Organization Report No.
84F0269

9. Performing Organization Name and Address
Goddard Space Flight Center
Greenbelt, Maryland 20771

10. Work Unit No.
992-41-00

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The method of retroduction, adapted from the doctoral thesis of Dr. A. Croce, relies on a process of dialectic questioning that begins with the information sought, proceeds to *Given* items (either in the form of dimensions or limits of research), and to *Known* mathematical forms of analysis in design or to principles of study in research. Finally, analysis and synthesis are used to abstract the dialectic questions and to arrive at the information desired. This method is used to solve the engineering design problem of a beam and to determine why bolts and nuts vibrate apart. Both mathematical analysis and dialectic logical analysis are utilized. Results are provided of tests conducted to check the retroductive study of why and how nuts back off.

17. Key Words (Suggested by Author(s))
Bolt, Nut, Vibration, Dialectic, Retroduction

18. Distribution Statement
STAR Category 37
Unclassified – Unlimited

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
76

22. Price
A04

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1987