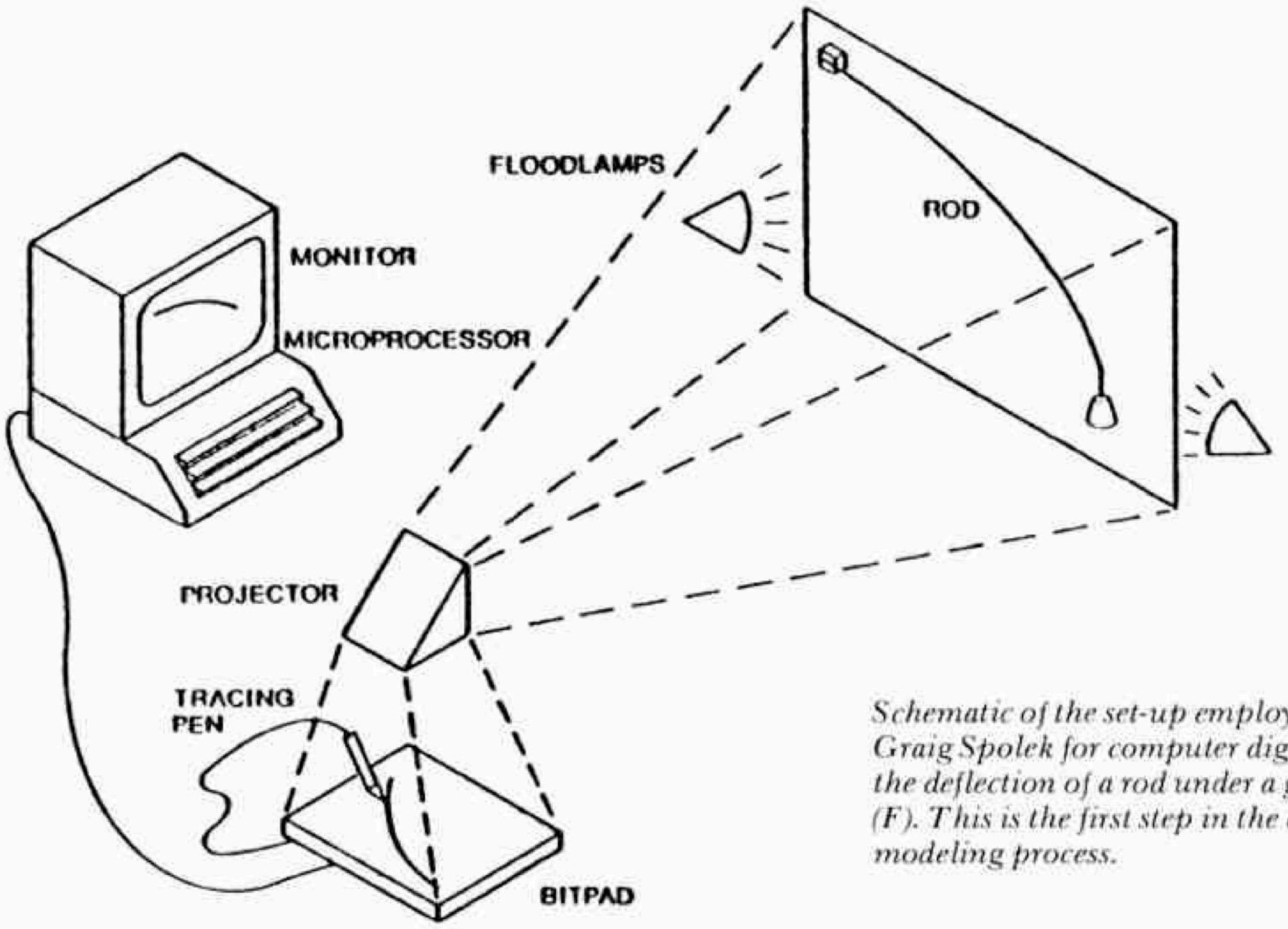
Where the Action Is

by Graig Spolek

About thirty-five years ago, your editor purchased his first fly rod. It was a nine-foot, three-piece model of Tonkin cane, manufactured by Horrocks-Ibbotson, replete with beautiful red windings. Profits from a newspaper route supplied the capital for the purchase, and after the sum of five dollars and ninety-five cents had changed hands, the clerk advised that yes, the rod sure was a beauty and that it had great action. *We had read about action in the sporting periodicals of the day, but we weren't sure what the term really meant. From a perusal of these erudite journals, however, it was certainly clear that it was important to have a rod possessing good action. Now, according to our local sporting goods clerk, at last we had one! More than three decades (and a few rods) later, we're still not sure what the term action really means when it is used to describe a physical or mechanical property of a fly rod. Furthermore, I'm sure that there are many anglers out there who are in the same boat. Action has been, and still is, a very nebulous descriptor. Like the weather, anglers talk about it, but nobody has ever done anything about it—that is, offered us a precise definition of the term or developed a scheme whereby one can accurately quantify the physical/mechanical properties of a fly rod. Enter Graig Spolek, associate professor of mechanical engineering at Portland State University. Thanks to Spolek's expertise in the application of differential equations to mechanical systems and some novel computer modeling techniques, a rather straightforward method has been developed to quantify the mechanical behavior of a fly rod. But we'll let Spolek tell you all about it in a two-part series on this topic, which follows. Part I defines terms and describes the method he developed for accurately quantifying a fly rod's casting characteristics. In Part II, with his rating scheme firmly in place, he quantitatively compares the mechanical characteristics of nineteenth-century fly rods with those of the twentieth century. Professor Spolek's work in this area is of landmark stature. He has broken new ground in a garden whose soil has lain fallow for years. Our hat is off to him.*



Schematic of the set-up employed by Graig Spolek for computer digitization of the deflection of a rod under a given load (F). This is the first step in the computer modeling process.

Power and *Action*

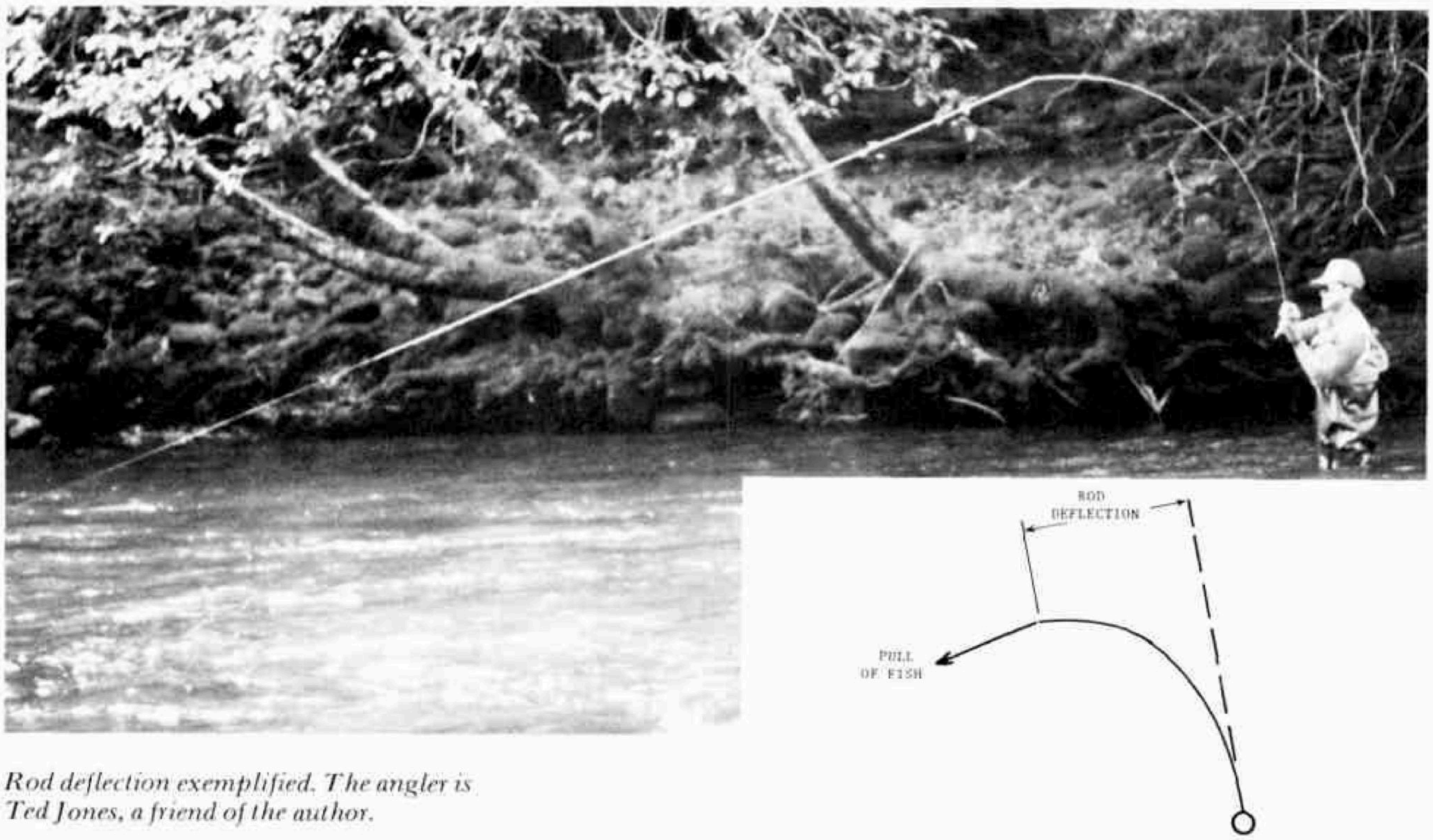
The words conjure up images of sleek, streamlined racing-machines noisily careening around corners at breakneck speed. *Power* and *action*. These and similar words have been routinely used for years by anglers and angling writers to describe the mechanical behavior of fly rods.[1] But what do these terms really mean? For example, *action* has been used to describe both the static curve of a rod deflected under a load (e.g., bent when playing a fish) and the dynamics of a rod's casting speed (i.e., fast or slow action). Furthermore, I'm sure we've all hefted a high-quality cane or graphite rod, wiggled it back and forth, and remarked to our spouse, fishing friend, or anyone within earshot, what wonderful *action* so-and-so rod has—and boy, what terrific *power!* Both terms are imprecise when used in describing the mechanics of a fly rod. They have absolutely no quantitative basis and are generally used in a very subjective, unscientific fashion—ofttimes enshrouded in a blanket of very dense fog. So how can we accurately describe the mechanical behavior of a fly rod? Anglers apparently do want to quantify, for a particular rod, deflection to load and casting speed. Speaking from a mechanical engineer's point of view, this can be most easily done by forgetting about the fuzzy words (power and action) and using the terms *stiffness* and *frequency*. These terms are used by engineers because they have precise meanings and are directly related to mathematical equations. It is the intent of this paper to explain to fly casters how *stiffness* and *frequency* can be used *apriori* to predict a rod's casting performance. Although these terms do not evoke as sensational imagery as *power* and *action*, they are, as we shall see, much more useful.

Stiffness

We intuitively think of the stiffness of a spring as some measure of how hard we need to pull on the ends of the spring to produce a certain amount of deflection. The fly rod acts in the same way as a spring when it resists the line pull due to the flight of a fish (or when our line gets snagged in a tree): the greater the pull, the greater the deflection of the tip. The stiffness of either the fly rod or spring is just the pull or force required to produce a given deflection. The deflection of a rod is necessary to absorb the shock put on a leader by a lunging fish, and the rod absorbs that energy so that the leader does not break. But the force causing the deflection depends on the size of the fish and the angler's urgency in turning that fish before other impediments—such as snags or fast water—enter the picture. So if we visualize the rod acting as a spring that aids us in landing a fish, then its stiffness becomes a measure of that performance.

We must be careful how far we carry the spring analogy, however, because there are major differences between the behavior of a rod and a spring. The first difference is that the rod bends while the spring stretches. The bent rod demonstrates the beauty of a smooth curve, enhancing the beauty of the rod itself. The shape of that curve, the curve of the deflected rod, has become one of the signatures of a rod's design. We have all heard comparisons of parabolic actions and tip actions, perhaps not recognizing that the rod curvature was being described. More precisely, the stiffness of the rod is being defined. Or, even more precisely, it defines the variation of the stiffness from the butt to the tip, the "stiffness profile" as identified by Don Phillips.[2] So when authors use *action* as a rod characteristic, they mean the same thing as *stiffness profile*, a more technical term that shows up as the rod curvature during a static load.

The other major difference between spring stiffness and fly rod stiffness is that while the stiffness of a spring remains constant, no matter how much deflection has occurred, the stiffness of a fly rod does not remain constant. This fact seems to be unknown to or ignored by rod manufacturers. If for purposes of design, the fly rod is treated as a cantilever beam, which is nothing more than a rod held at its butt with a load on its tip, then there are simple equations that can be used to calculate the relationship of rod stiffness and curvature. Garrison and Carmichael cite these equations for determining the dimensions of bamboo rods, but these equations were originally developed for beams of steel and concrete, items that don't deflect much and aren't supposed to. These equations *are not valid for flex-*



Rod deflection exemplified. The angler is Ted Jones, a friend of the author.

ible beams, especially for those that have tip deflections more than 25 percent of their length! Of course all fishing rods fall into this category, so the equations really shouldn't be used. Why? Simply because these equations indicate the springlike behavior of rods with a constant stiffness, but the stiffness of actual rods increases dramatically as they are bent more and more.

In order to test the significance of this effect, a laboratory test was carried out to accurately measure a rod's deflection and its curvature. A rod was clamped horizontally by its butt and a weight was hung from the tip. The rod's curvature was scanned automatically by a computer that then calculated the stiffness, which was defined as the weight of the load divided by the vertical tip deflection. When light loads were suspended from the rod tip, the measured rod stiffness was reasonably close to that predicted by the aforementioned simple equations. However, the rod's stiffness was found to increase by a factor of seven or eight when the rod was heavily loaded. The simple equations introduce significant error.

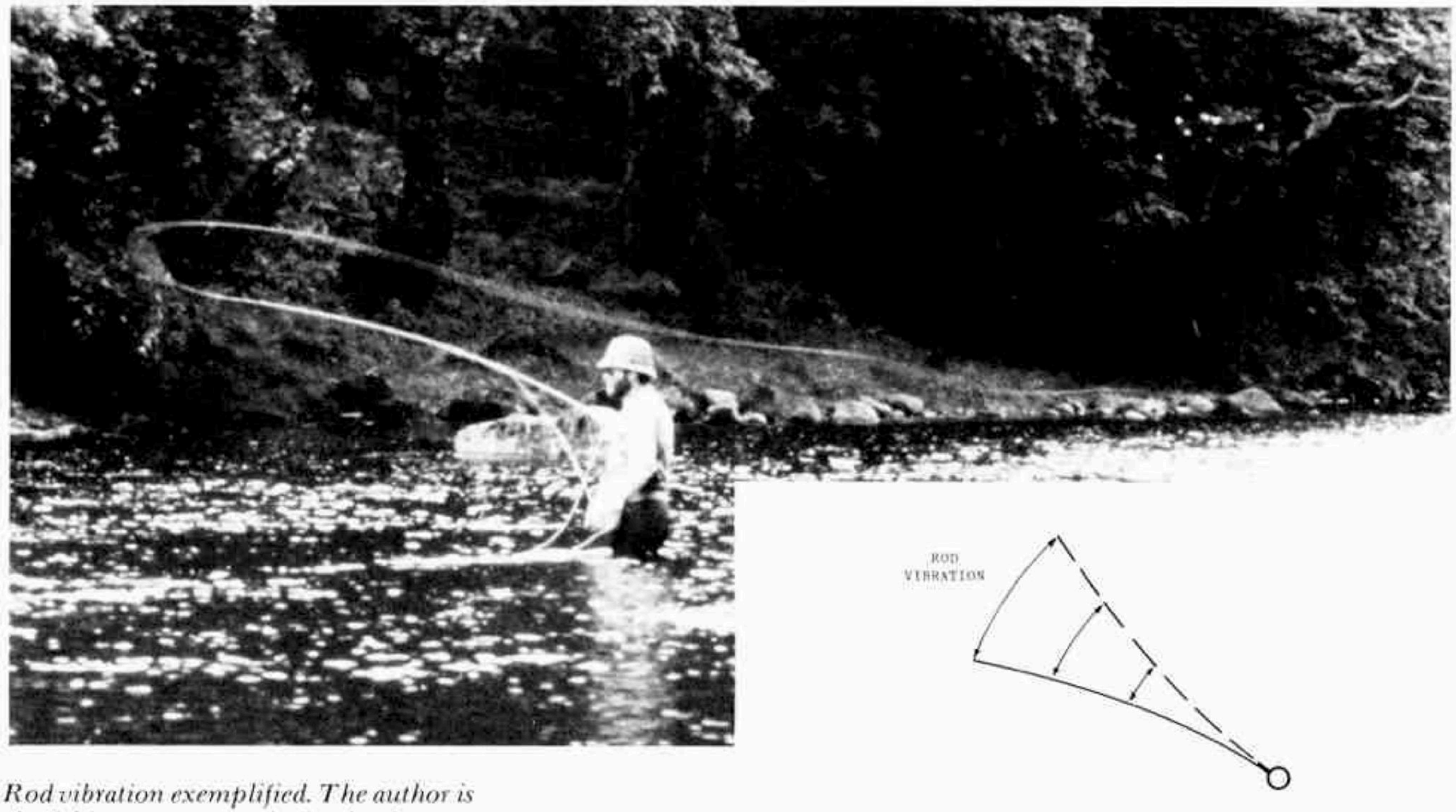
The laboratory test was performed to demonstrate the inaccuracy introduced by the constant stiffness equations and to test the capacity of a new set of equations that were derived specifically to predict the deflection and curvature of a heavily loaded rod. The new equations are somewhat complex, and a computer must be used to solve them (the details of the equations and their solutions are published in scientific literature).[3] The large deflections predicted by these mathematical equations were accurate when compared to those measured for actual rods. Hence, the mathematical model of a rod was used with confidence to test the effect of varying design features of rods. Each design feature was changed independently of all others, and the effect of that change on the rod's stiffness was determined. The results of these computer-generated rod designs were interesting and not always obvious.

One of the marketing features of any rod is its length. Length has a profound effect on rod stiffness. As one would expect, shorter rods are stiffer than longer rods. Specifically, the stiffness varies inversely with the length squared. So a rod that is half as long as another will be four times as stiff.

Another rod feature that is very important to rod designers, but often ignored by the rod buyer, is the diameter of the rod. Since all rods are tapered, we must be more specific about where we measure the rod's diameter. For purposes of comparison, let's separate diameter effects from taper effects. For instance, consider the butt diameter to be a convenient measure of the typical rod diameter. The rod's stiffness varies dramatically with changes in the diameter, even more dramatically than length effects. Again, from deduction, we expect that the rod with a smaller diameter will be less stiff. What we might not expect is that the stiffness varies with the diameter raised to the fourth power. This means that a rod with half the diameter of another will be one-sixteenth as stiff.

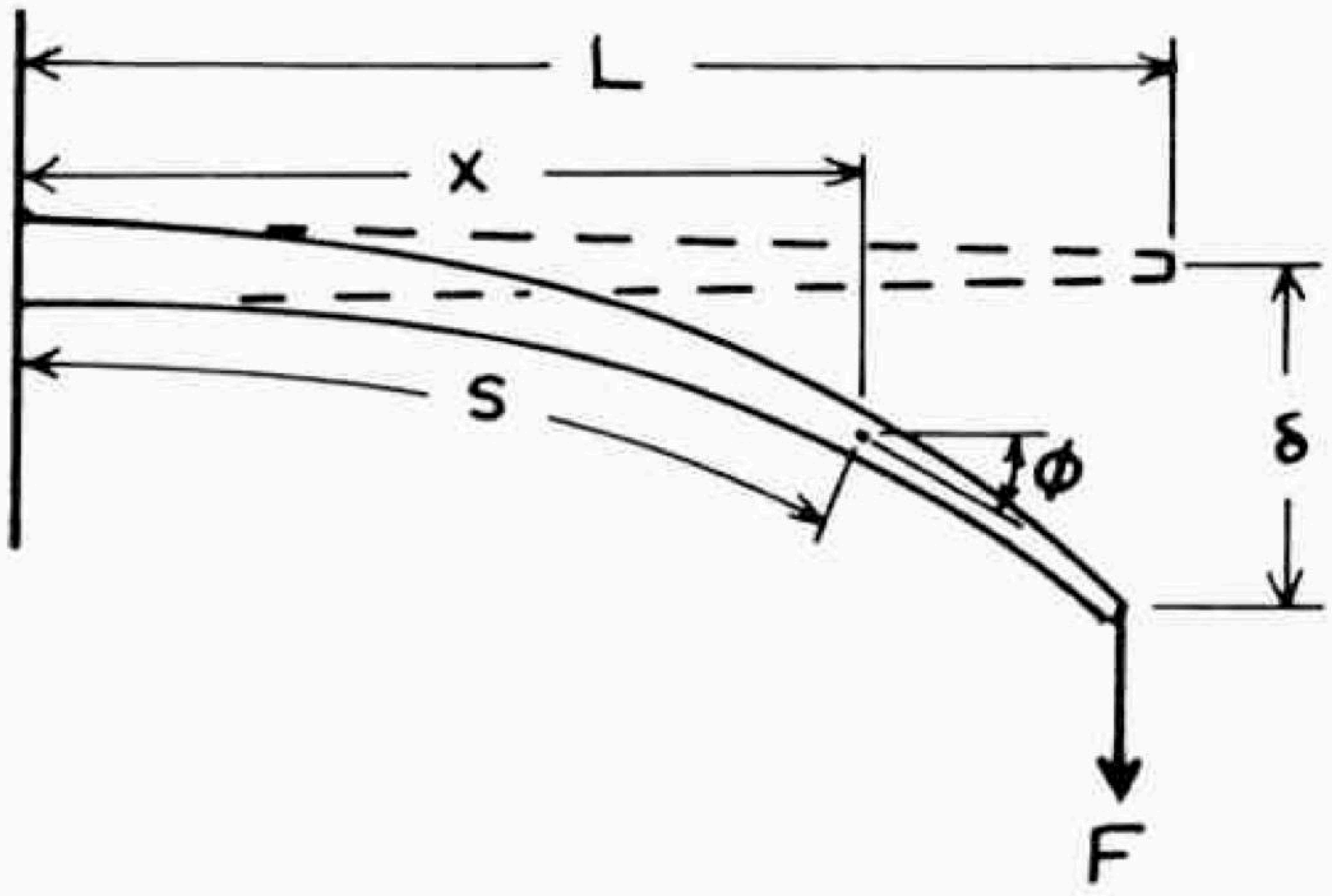
Once we identify the importance of diameter on stiffness, we logically conclude that the rod taper will also significantly impact on the stiffness. That, indeed, is the case. For uniform tapers, where the rate of diameter decrease from the butt to the tip is constant, we can quantify the taper as the ratio of the tip diameter to the butt diameter. As this ratio increases, the stiffness increases. For example, if the taper ratio is increased from one-tenth to two-tenths with the same butt diameter, then the stiffness increases by a factor of two to one. The exact amount of this stiffness increase is valid only for the example cited, but one can get an idea of the importance of this design factor. It must also be recognized that the stiffness effects will differ for compound tapers.

The final factor affecting rod stiffness is the inherent stiffness of the material that composes the rod. In our experience, we have come to expect differences in butt diameter and taper for rods of about the same length and stiffness when they are constructed of bamboo, fiberglass, or graphite. The manufacturers vary those design features to achieve the desired performance, part of which is the stiffness. They do so to compensate for the material stiffness, which is its modulus of elasticity and is often referred to simply as the *modulus*. For example, since the modulus of graphite is much larger than that of



Rod vibration exemplified. The author is fly-fishing on a stream in Scotland.

1. Geometry - Tapered Cantilever Beam



L = Length

F = Force

δ = Tip Deflection

2. Simple Linear Equations

$$\frac{d\phi}{dx} = \frac{F\,(L - x)}{EI}$$

$$\delta = \int_0^L \phi\,dx$$

E = Modulus of Elasticity (constant)

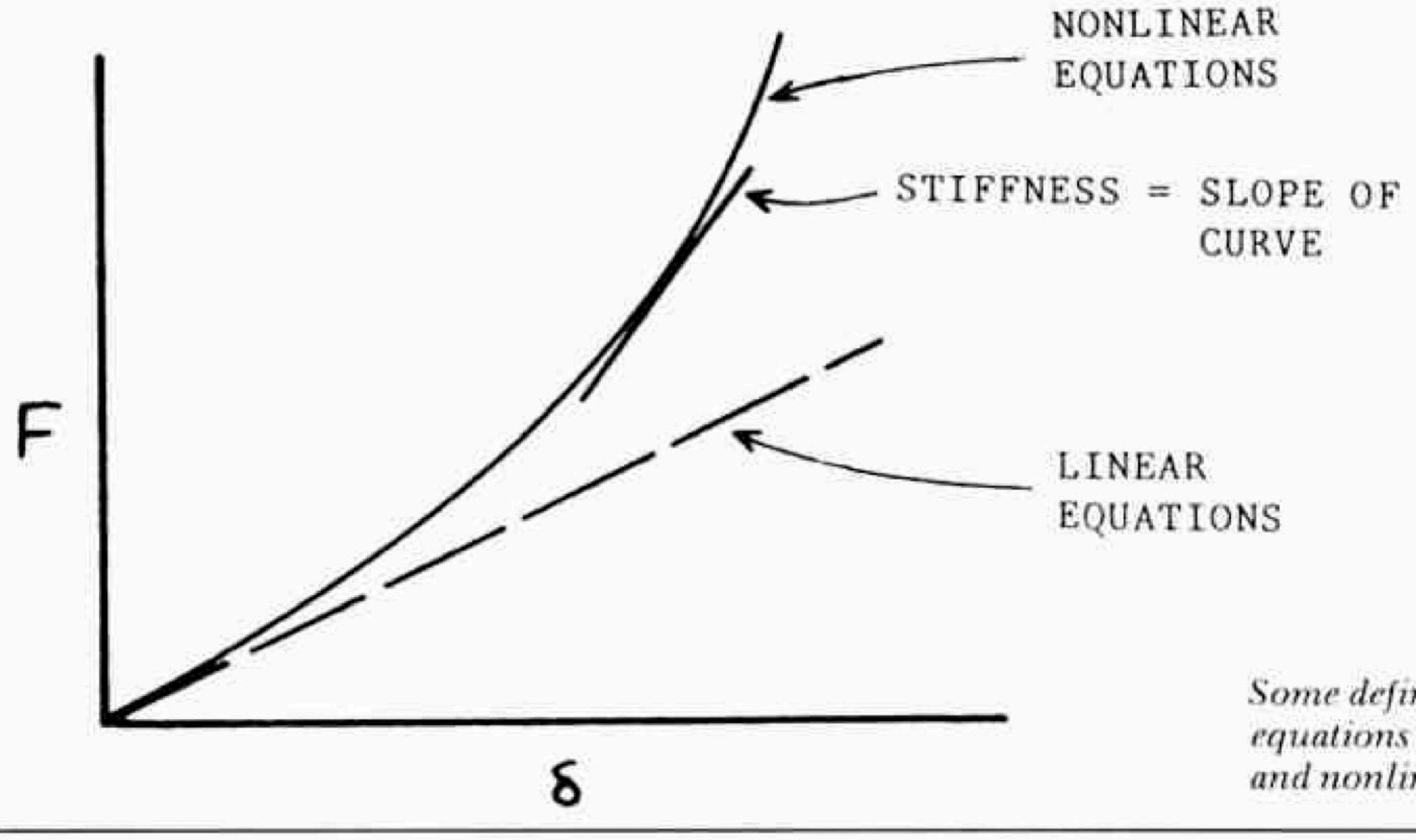
I = Moment of Inertia at distance x

3. Nonlinear Equations

$$\frac{d^2\phi}{ds^2} = \frac{1}{I}\,\frac{dI}{ds}\,\frac{d\phi}{ds} + \frac{F}{EI}\cos(\phi)$$

$$\delta = \int_0^L \phi\,ds$$

4. Results



Some definitions and the differential equations that describe both the linear and nonlinear models (see text) fiberglass, the diameter of the graphite rod is reduced proportionately to produce the same stiffness for the two rods. The stiffness of rods varies linearly with the modulus, so a rod with a material that has twice the modulus of another will be just twice as stiff.

We can now summarize that a given rod's stiffness will depend on its length, butt diameter, taper, and material. Specifically, the stiffness of a rod depends on the variables discussed according to the relationship:[4]

$$\frac{(\text{Modulus})\,(\text{Diameter})^4}{\text{Length}^2}$$

We can now also conclude that a rod's stiffness will not remain constant but will increase significantly as it bends more and more. Thus, when we try to anticipate how a rod will bend when turning a heavy fish, we are able to compare two different rod designs.

Frequency

We must do more than reel in lunker trout; we must also make pinpoint casts with delicate flies to entice them. Fly-casting is a dynamic activity, fighting a fish is a more-or-less static activity. A rod's dynamic behavior is characterized by its frequency, or the speed at which it naturally vibrates.

All mechanical devices vibrate; the speed at which they vibrate is called the natural frequency. When the mechanical device is pushed back and forth at a frequency near its natural frequency, the device resonates and shakes wildly. For example, when we drive the old car with worn-out shocks over a washboard road at just the wrong speed, the car starts bouncing around like crazy. If we go a little faster or a little slower, there's no problem. In between we strike the resonance of the car's suspension with the frequency of the bumps in the washboard road.

Fly rods, being mechanical devices, also vibrate with a natural frequency. Actually, a fly rod can vibrate at very many natural frequencies, or harmonics, but we only need to concern ourselves with the lowest natural frequency because that is the one that controls the so-called casting action. The casting motion seeks to strike resonance within the rod. During a forward cast, the rod is loaded by both the weight of the line and the weight of the rod we are trying to accelerate. When the forward casting stroke is halted, the rod continues to move forward, its speed increasing until it straightens out. When it is straight, both the rod and the line being cast have their maximum speed. Since line speed controls the cast, this point of maximum speed is very important in predicting casting performance.

The line speed during casting depends on the natural frequency of the rod, all other factors being equal. A rod with a higher natural frequency will deliver greater line speed than one with a lower natural frequency. This has been known to fly casters for a long time, for they developed descriptions of fly rod natural frequency: A fast action means high natural frequency, a slow action mean low natural frequency. We can begin to understand how these terms cause confusion though. *Action* was used by Janes and Engerbretson to indicate rod stiffness; Engerbretson uses *feel* to describe frequency. Garrison and Carmichael use *wave linear action* for frequency.[1]

Frequency is a much more useful term for describing a fly rod's casting characteristics, because it can be quantified. It can be measured experimentally or it can be predicted by mathematical equations. We have done both and discovered that the mathematical prediction was quite accurate. Once convinced of the validity of the mathematical equations, we again tested the various design features to determine their relative effects on frequency. Rather than presenting those specific findings below, the results will be generalized.

A rod's frequency depends on two factors: its stiffness and its weight (more correctly, the *amount of mass* and its *distribution*). The frequency of a rod increases as its stiffness increases. So those factors discussed previously (length, diameter, taper, and material) that increase the stiffness will increase the frequency, if they have no effect on the rod weight. Obviously, they all do affect the weight. The amount of material and its distribution in the rod are determined by rod length, diameter, and taper. The density of the material affects the weight. Because of these interactions, a rod's stiffness and frequency are not totally independent, but some design changes affect one more than the other. As a result, one cannot predict the frequency from the stiffness or vice versa. It would be possible, by properly adjusting the design variables, to produce two rods with exactly the same stiffness having different frequencies. Conversely, two rods with the same frequency could display different deflection under the same load.

Thus, we conclude that two separate quantities, *stiffness* and *frequency*, must be known for a given rod, to anticipate how it will perform in the field. These two properties embody the concepts used by previous writers when describing fly rod actions but have the advantage in that both have precise meanings. They can be measured or predicted for each and every rod. If values for stiffness and frequency were specified for available rods, soon we would feel as comfortable in using them as we are now in comparing rods for #5 or #7 lines, or contrasting slow, medium, or fast actions. The main difference in using *stiffness* and *frequency* as fly rod descriptors, in place of *power* and *action*, is that we would all be using common language.

In order to demonstrate, rather than speculate on, the importance of the terms *stiffness* and *frequency*, these quantities were measured for a wide variety of historic and contemporary fly rods. In the second article of this series, the results of those tests will be discussed. Specifically, the evolution of fly rod designs, in terms of their respective stiffnesses and frequencies, will be analyzed. The reasons for the shift to modern rod materials will then become clear. Furthermore, the understanding and use of the terms *stiffness* and *frequency* to describe fly rod performance will be employed as the basis for an objective rating scheme for fly rod performance. §

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1. For example, Edward Janes uses *power* and *action* (see appendix to the 1976 edition of Ray Bergman's *Trout*). Dave Engerbretson uses *action* and *feel*. See "Fly-Rod Actions," *Rod & Reel* (May/June 1982). Garrison and Carmichael use *wave linear action*. See *A Master's Guide to Building a Bamboo Fly Rod* (1977): p. 236.

2. Phillips, Don, "Another Dimension for Fly Rod Evaluation... Stiffness Profile," *Fly Fisherman* (June/July 1973).

3. Spolek, Graig, and Jeffries, Steve, "Analysis of Large Deflections of Fishing Rods," *Computational Methods and Experimental Measurements*, Springer-Verlag (1982). Copies of this paper can be obtained by writing to Professor Graig Spolek in care of the Department of Mechanical Engineering, Portland State University, P.O. Box 751, Portland, OR 97207.

4. The stiffness also depends on the rod taper, but that dependence cannot be expressed in a straightforward form. The dependence of stiffness on taper is nonlinear. The nearly linear dependence of the example used in the text of this paper was purely coincidental, but the taper values used to calculate that dependence are typical of those for fiberglass and graphite fly rods.

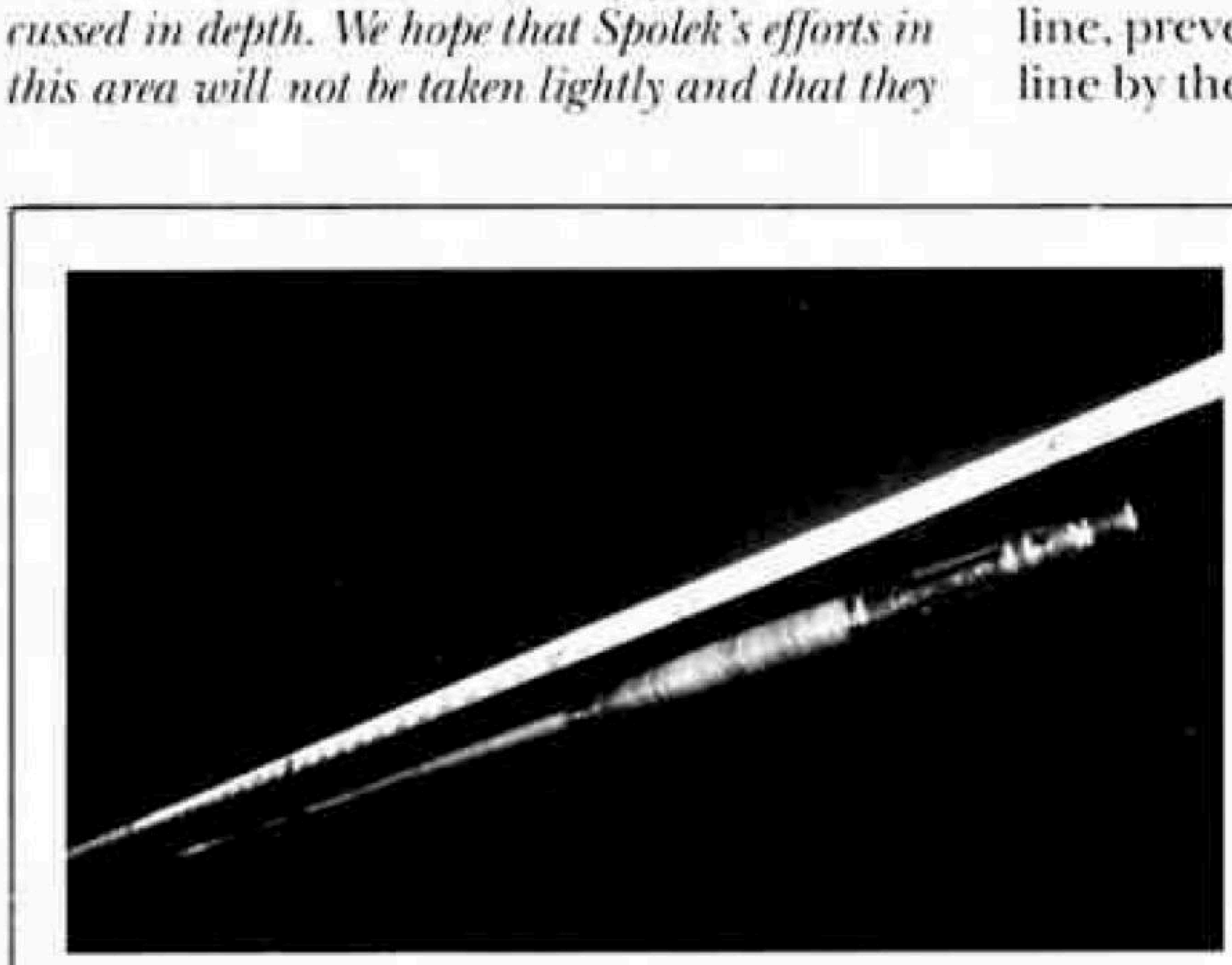
Where the Action Is: Part II

by Graig A. Spolek

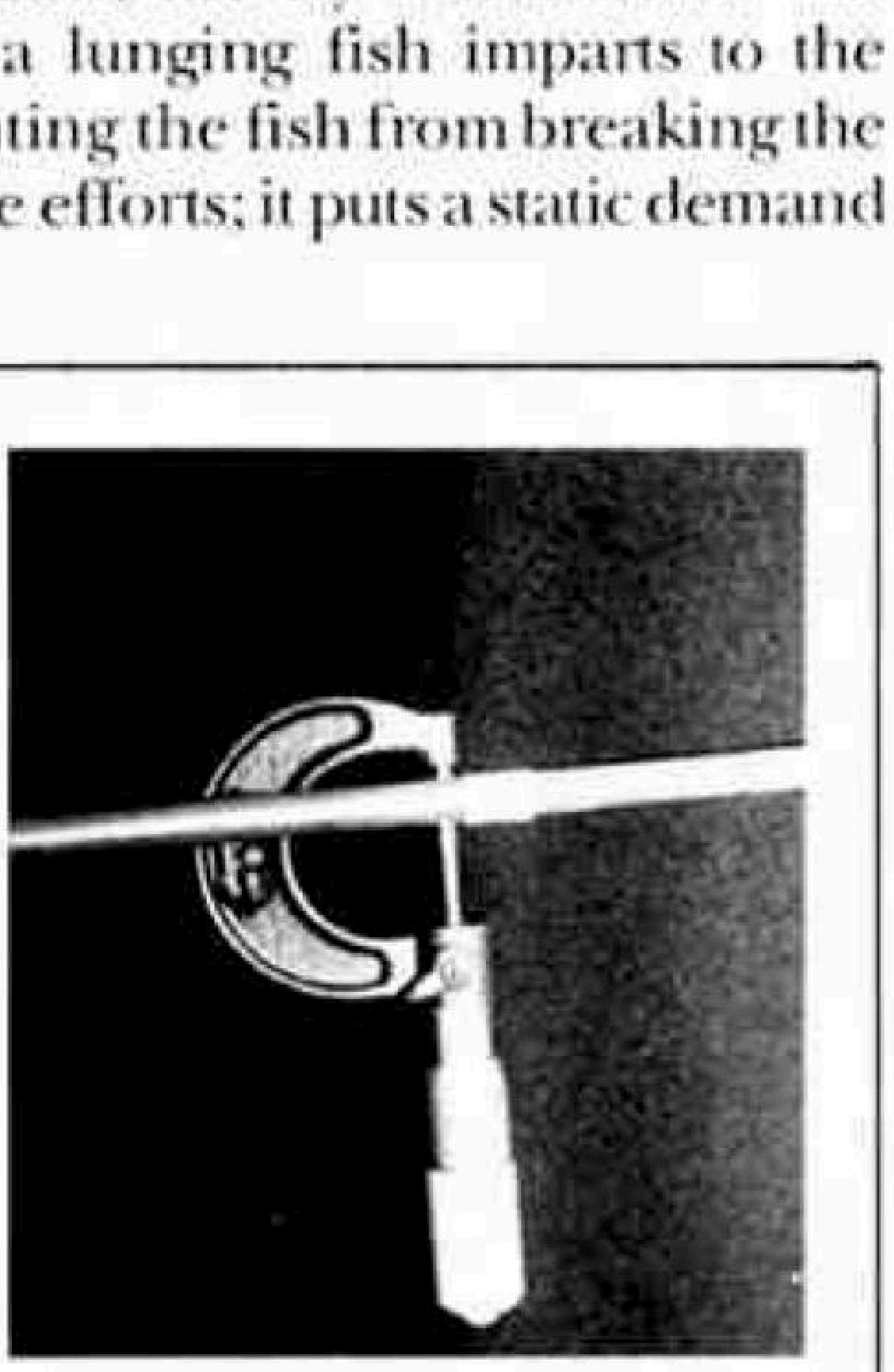
Having quantitively defined the mechanical properties of fly rods in terms of stiffness and frequency for the first part of his series (American Fly Fisher, *vol. 13, no. 4), Graig Spolek now compares these properties in contemporary fly rods with those of the nineteenth and early twentieth centuries. According to Spolek's experimental studies, rod stiffness has not changed substantially in the last century, while rod frequency has increased dramatically. Spolek also suggests that now, with a method for accurately measuring the mechanical behavior of fly rods in hand, a new, more accurate and highly quantitative system for the rating of fly rods could easily be developed: a numerical system with scales for both stiffness and frequency. After a brief introduction, the details of his unique experiments are described, and the results, particularly as they relate to the evaluation of the fly rod, are discussed in depth. We hope that Spolek's efforts in this area will not be taken lightly and that they will have considerable impact on fly fishers as well as rod manufacturers. It's time to take action on "action." Once and for all, let's rid ourselves of this imprecise, overused fly-rod description and champion the cause of stiffness and frequency.*

Evolution of the Fly Rod

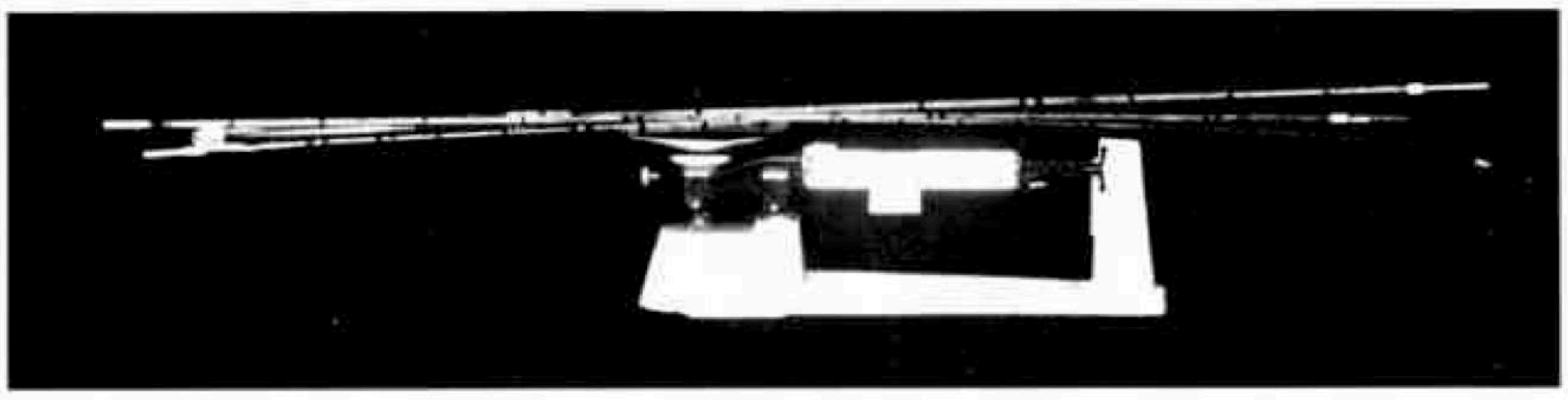
In the first article in this series, arguments were made that the mechanical performance of a fly rod can be completely described by knowing just two factors: stiffness and frequency. These two factors were used because they have precise meanings and indicate the way a rod will respond to the two main demands placed on it during fishing: fish-fighting capacity and casting effectiveness. When one is fighting a fish, the fly rod absorbs the shock that a lunging fish imparts to the line, preventing the fish from breaking the line by these efforts; it puts a static demand on the rod. The rod's ability to absorb the energy of the fish's fight is characterized by the stiffness. One selects rod stiffness according to the size of the fish sought, choosing a rod with high stiffness for salmon, and choosing a more limber rod for trout. The rod's frequency, on the other hand, reflects its ability to be cast, the dynamic activity of fly-fishing. During casting, the rod is loaded by the caster's motion, but it unloads on its own and at its own speed. The rod's frequency is a measure of this unloading speed. The rod with a high frequency will deliver the high line-speed that is necessary for long-distance casting. The high frequency often makes the rod more difficult to cast and complicates delicate fly presentation; thus, sometimes a rod with a lower frequency is selected when fly presentation or casting ease is more important than distance casting.



The length of each rod was measured with a tape measure.



Rod diameters were measured with a micrometer. The rod length was divided into ten equal segments, marked with white tape, and diameters were measured at each mark in order to determinte the rod's taper.



The weight (or mass) of each rod was measured with a triple beam balance.

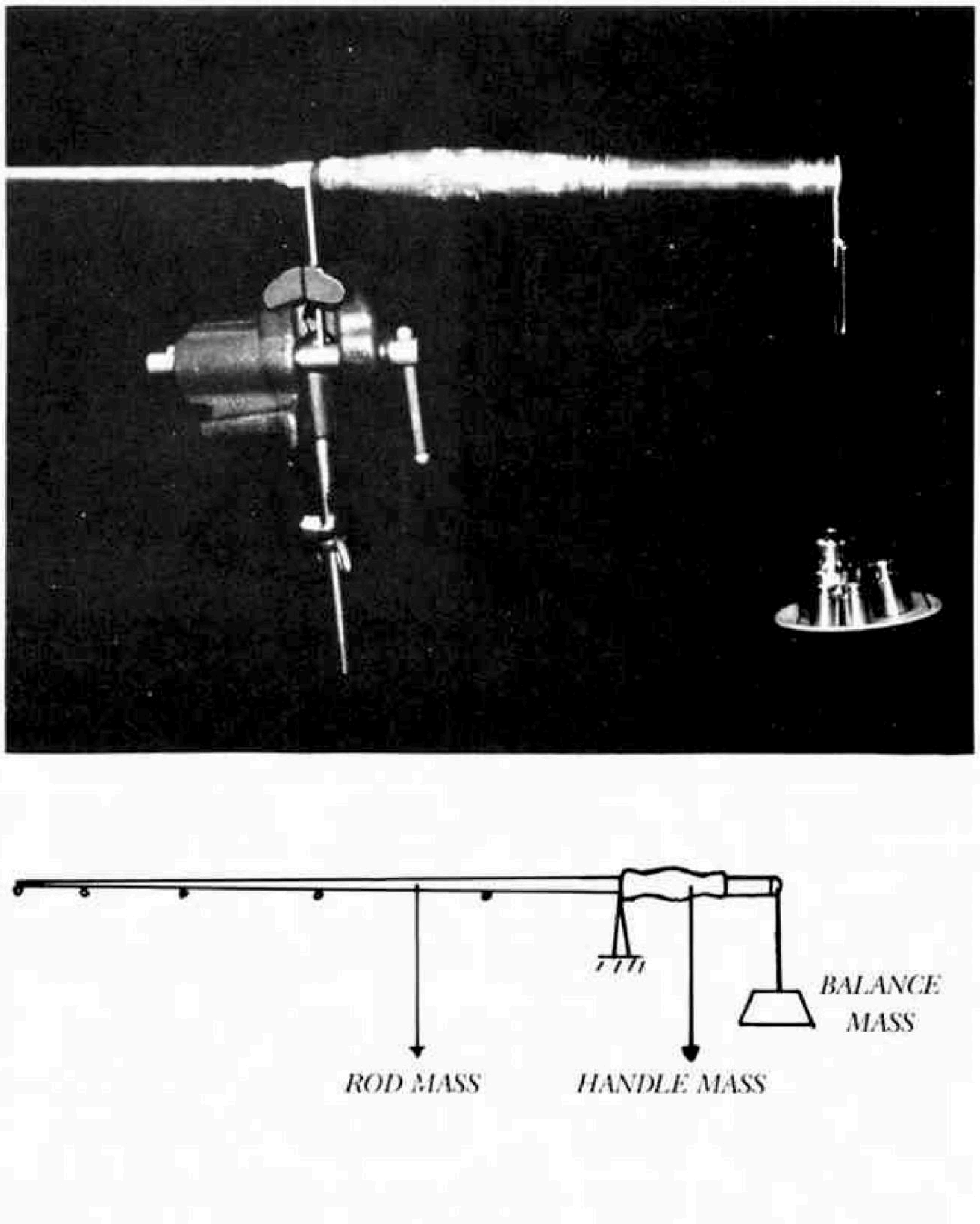
Today's fly rod offers us the choices of sophisticated design: high or low stiffness and high or low frequency. Generally, then, we choose a rod depending on the quarry we seek and on our casting skills. This latitude of choice has not always been available. Early fishers used rods that were very crude, in some cases no more than cut saplings. As fly-fishing became more popular, the rods became much more sophisticated. Rod materials were selected for their strength and the ease with which they could be turned into rods. Such hardwoods as white ash, ironwood, lancewood, and greenheart became popular choices for solid wood rods; these were usually turned on a lathe. They were strong, flexible, and very handsome; but they suffered in that their solid bodies contributed little to their function besides excess weight. The logical progression of rod development was the use of a material that concentrated its strong fibers near the outside surface of the rod; a suitable candidate for this was bamboo. While raw bamboo exhibits this property, the diameters and tapers of the cane are at Mother Nature's whim and are not always the best for fly rod performance. More uniform mechanical properties for rods were obtained by cutting strips of bamboo, tapering them individually, and gluing them together. Rod designs using four-strip, five-strip, six-strip, and eight-strip construction were tested with varying success; the six-strip design eventually emerged as the most popular. Initially, bamboo obtained from the Calcutta region of India was used, but then the bamboo from the Tonkin region of China proved to have superior qualities. Years later, even the Tonkin cane rods were improved by an impregnation process that increased the rods' durability and perhaps even their performance.

Fiberglass rods were the first to be constructed solely of synthetic materials. Initially, these rods were of solid fiberglass, but like the solid wood rods, they were too heavy. Thus hollow fiberglass rods were soon developed, and these revolutionized the fly rod industry. They could be manufactured at much lower cost than bamboo rods, and they possessed very consistent properties—more consistent than bamboo with all its natural variations. Furthermore, it became easier for rod designers to obtain the stiffness and frequency they sought, because a rod's length, diameter, and taper could be easily controlled. Although a major one, the only problem with the hollow fiberglass rod was its weight; the stiffness-weight ratio limited the frequency that could be achieved in a rod of reasonable mass and length. Modern graphite rods obviate the problem. Using graphite of varying density and modulus, today's rod designer can create almost any stiffness and frequency in a rod that a fly fisherman desires.

In short, then, because of the materials and the limited technology available, early fly rods had the appropriate stiffness for handling a particular range of fish, but a rod's frequency could not be precisely controlled. More specifically, I would guess that the early rods had much lower frequencies than their modern counterparts. The purpose of this article is to describe the process by which I tested this hypothesis. I conducted an experimental study to measure rod behavior. I will explain how these tests were performed and present the results of the test so that you can draw your own conclusions on whether you agree with my hypothesis. Finally, I will propose a new rating scheme for fly rods that is more consistent and complete than the current method.

Rod-Testing Procedure

Testing the changes that have occurred in fly rods requires, of course, a collection of rods of different ages. Such a collection was assembled (see table on page 7). In order to avoid comparing apples with oranges (as much as possible), the rods chosen had similar lengths and similar stiffnesses (e.g., what would be considered trout rods rather than salmon rods). The rods had been constructed with a variety of construction techniques and materials. The primary source of rods was the American Museum of Fly Fishing, whose generous loan of rods made this study possible. A few rods were also selected from the author's collection, primarily to provide more samples of modern rod-technology. In all, sixteen rods were tested, but two of these proved to have the very high stiffness of salmon rods, so they were not used for other comparisons. A complete description of each rod and its characteristics is given (see table). The overall objective of the test program was to determine the mechanical performance of each rod. In



To find the rod mass (the mass of the portion of the rod extending beyond the handle), the rod was balanced on a knife edge. Weights were then suspended from the rod butt until the rod just balanced. Once the balance mass and the rod length were determined, the rod mass could be calculated.

order to do this, several different measurements were made. Physical properties, such as length, weight (mass), and taper, were measured. Rod stiffness was also determined as well as the change of stiffness for each rod (see the *American Fly Fisher*, vol. 13, no. 4, for the first article of this series and for a discussion of this stiffness change). Also, the dynamic performance of each rod was determined by measuring the rod's natural (or resonant) frequency, and the amplitude of vibration at this resonant condition.

Physical Properties

Length: A tape measure was used to measure the *overall length* of the rod (see photograph). Of greater importance for mechanical performance is the length of the rod that actually undergoes flexing during casting and fish-fighting. Since the enlarged handle essentially eliminates flexing of this portion of the rod, the *rod length* was measured from the winding check to the rod tip. The rod length was then divided into ten equal segments, and each segment was separated by a white tape marker. These ten-percent marks are illustrated in the accompanying photographs.

Taper: For each rod, the diameters were measured (with a micrometer) at the rod butt, the tip, and at each of the ten-percent positions. For cane rods, the diameter was measured across the flat surfaces on which the guides were mounted (see taper plots on page 9).

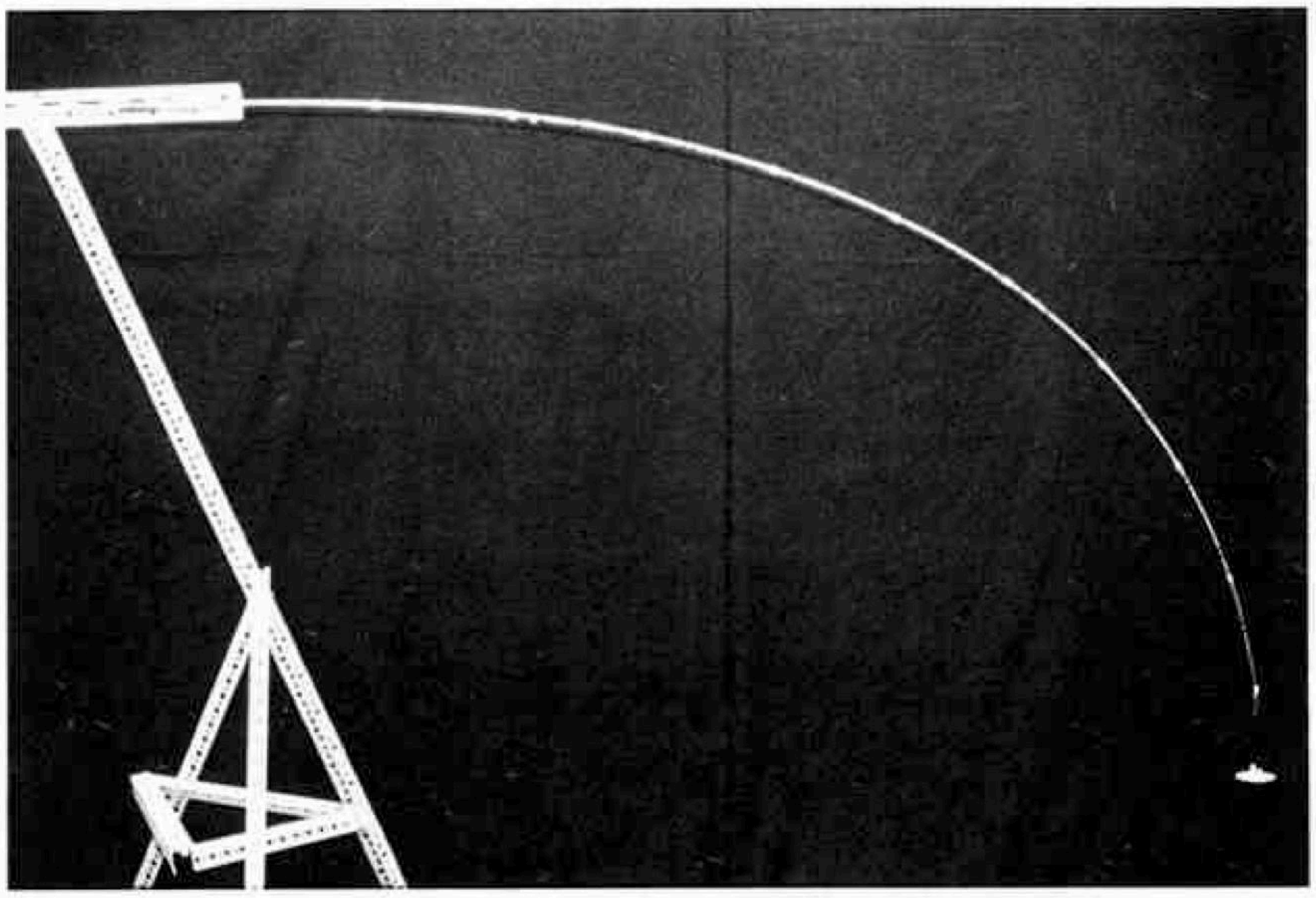
Weight: The overall weight *(overall mass)* for each rod was measured with a triple beam balance (see photograph). Again, it is the mass of the portion of the rod extending beyond the handle that is of greatest importance for mechanical behavior. This *rod mass* could not be measured directly, since the handle could not be removed from the rod. Therefore, the following indirect method to approximate the rod mass was used:

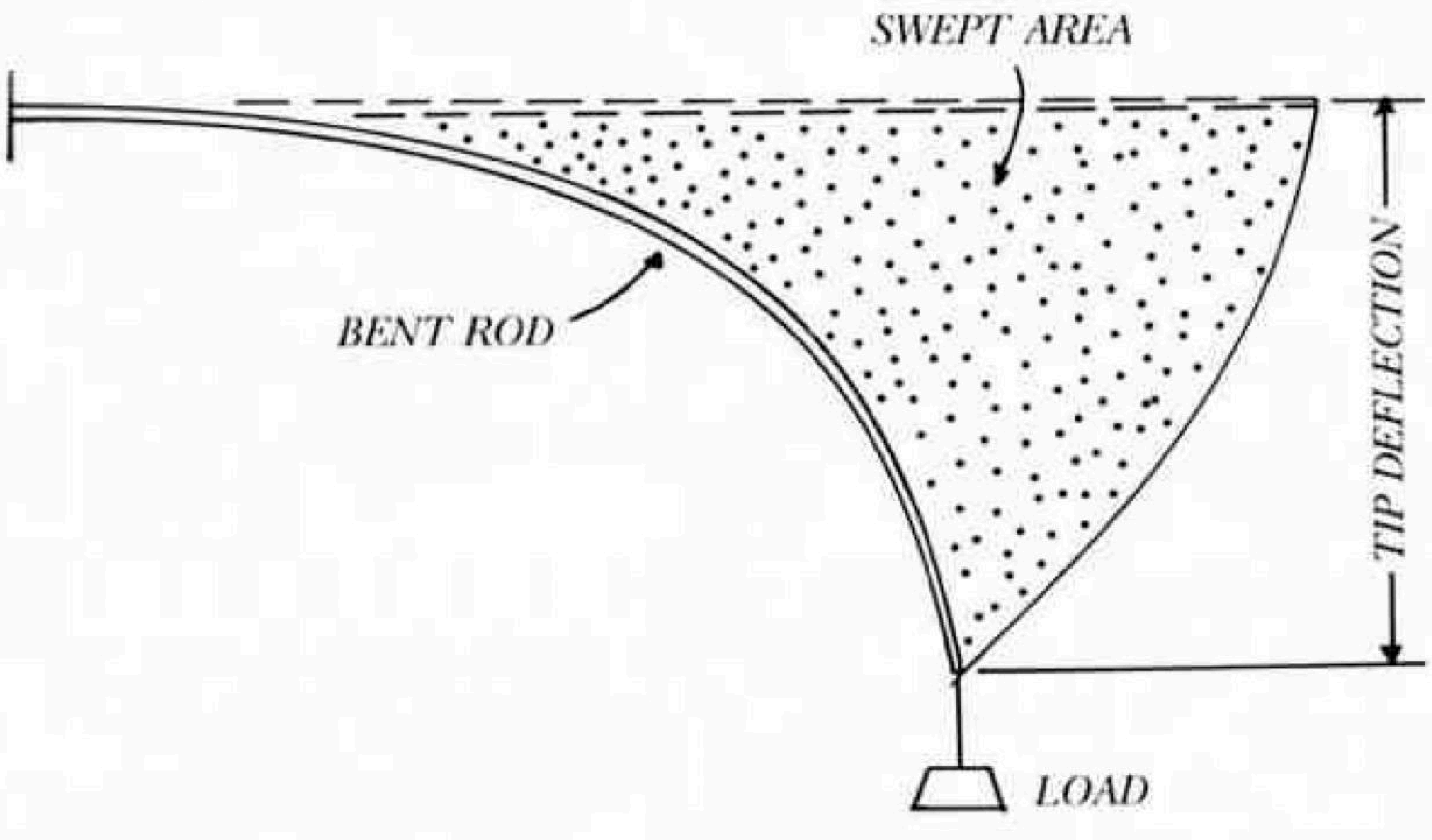
Each rod was balanced on a knife edge positioned right at the base of the handle (see accompanying illustration). The rod was balanced by suspending weights from the butt of the handle. By finding how much weight *(balance mass)* was necessary to just balance the rod on the knife edge, the rod mass could be calculated. This calculation required two major assumptions: (1) the handle is of uniform diameter and density, and (2) the rod taper is uniform. It is clear that these two assumptions aren't really accurate for some of the rods, but the errors introduced aren't enormous, either. The method was tested by using the procedure to calculate the rod mass for an expendable graphite rod. The handle was then cut off and the rod mass was measured directly. The difference between the two methods was less than three percent. So this procedure for calculating the rod mass should be adequate to allow relative comparisons of rods even if the values are not exactly correct.

Stiffness

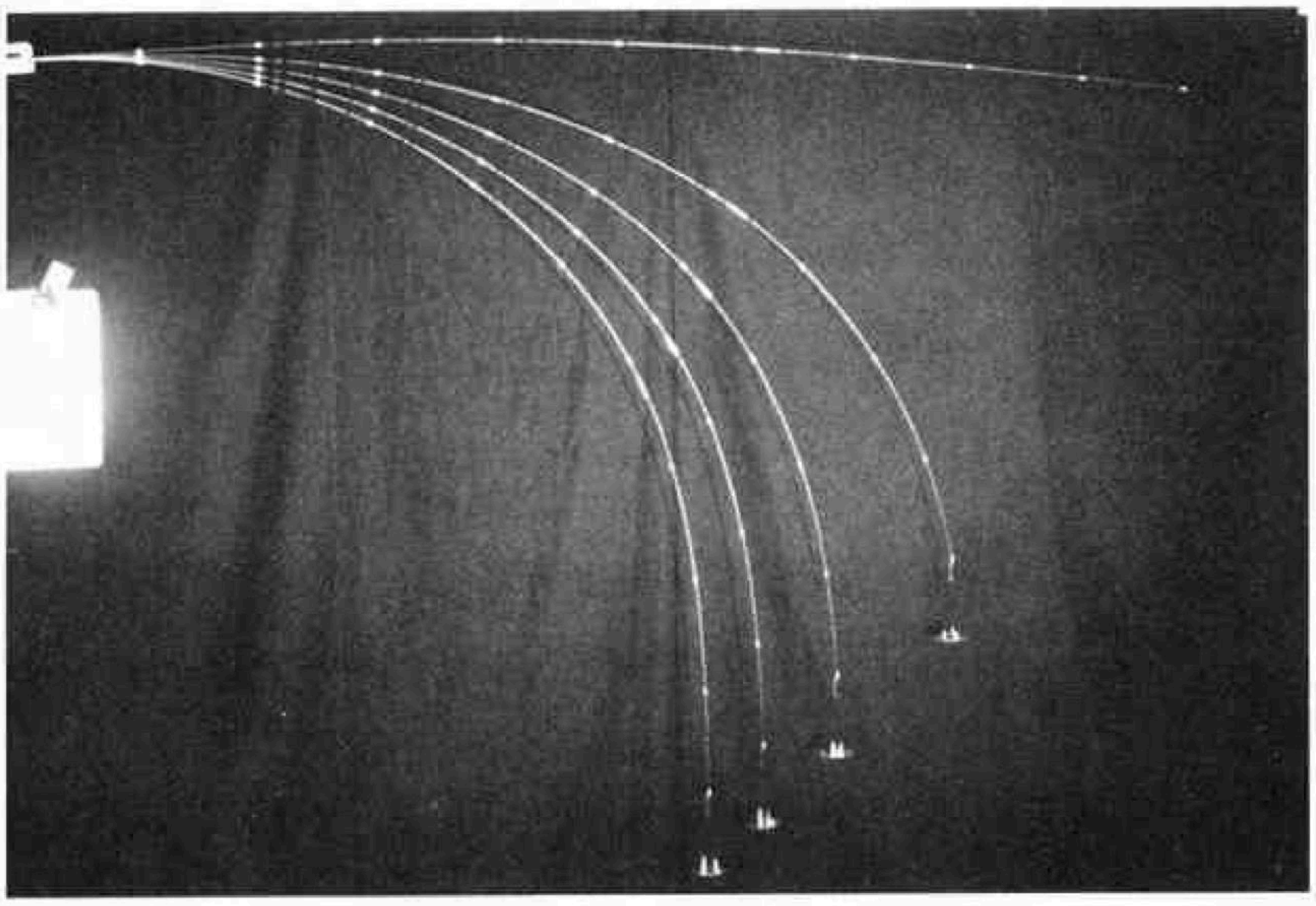
The stiffness is defined as the amount of load applied to the rod to get a given amount of tip deflection. So the test procedure is essentially just that: load the rod and measure the tip deflection. A special test fixture was constructed to hold the rods by the butt (representing the way they are held during fish-fighting). A rod was clamped at its butt so that the unloaded rod was cantilevered horizontally. Once the rod was mounted, the angle of the butt was adjusted so that the butt and tip were in the same horizontal plane. This adjustment was necessary to account for warp in some rods and for the deflection due to the rod's own weight.

During testing, the rod was loaded by placing lab weights onto a pan hung from the rod tip. The loading caused the rod to bend with the tip deflecting downward (see illustration). The amount of weight was recorded, and the bent rod was photographed. The photographs were then analyzed by computer to calculate the rod deflection. Two methods of calculating rod deflection were used: (1) the vertical tip deflections were measured and then divided by the rod length to yield deflections normalized for all rods, and (2) the areas swept by the rod during deflection were measured and then divided by the

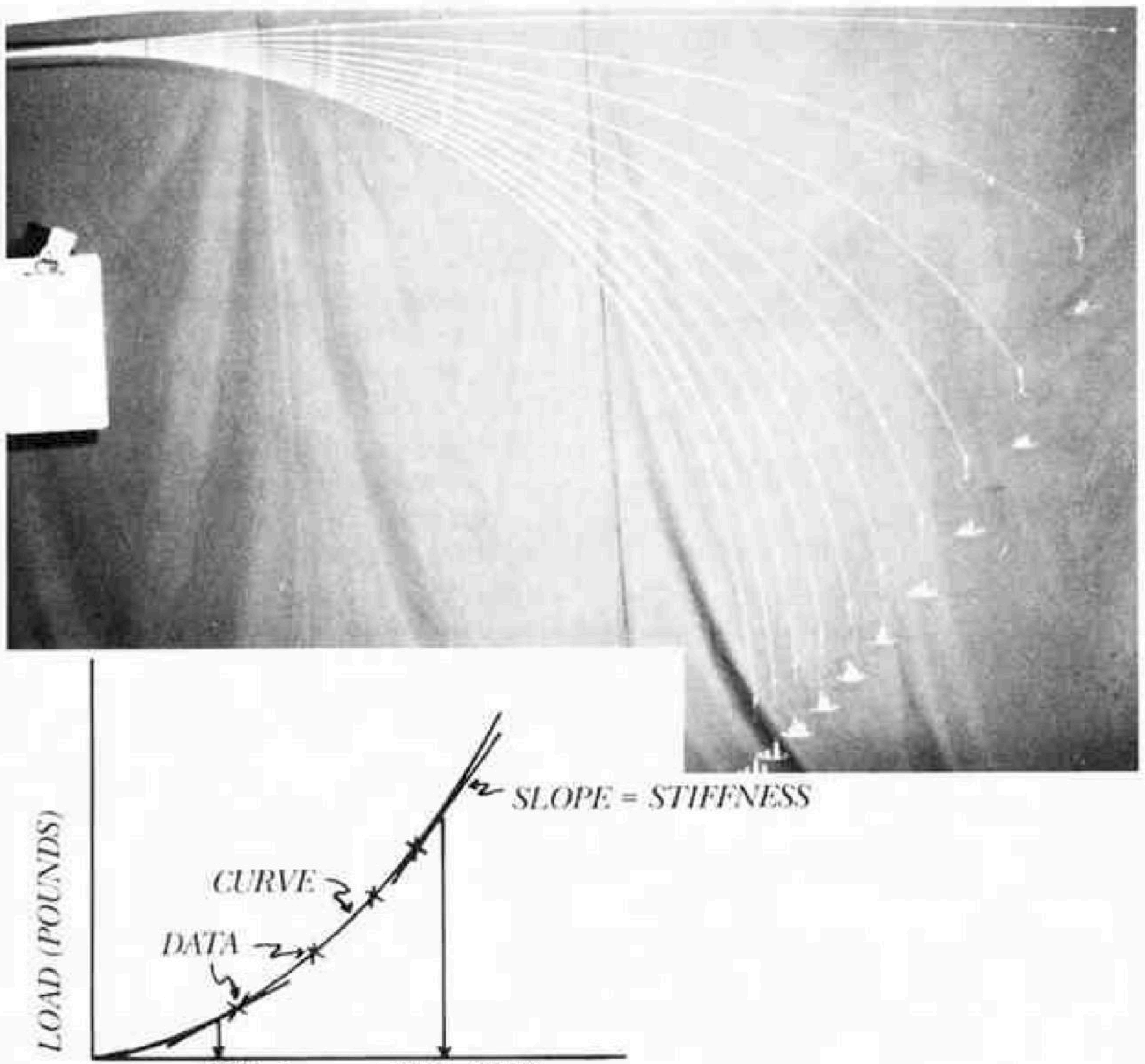


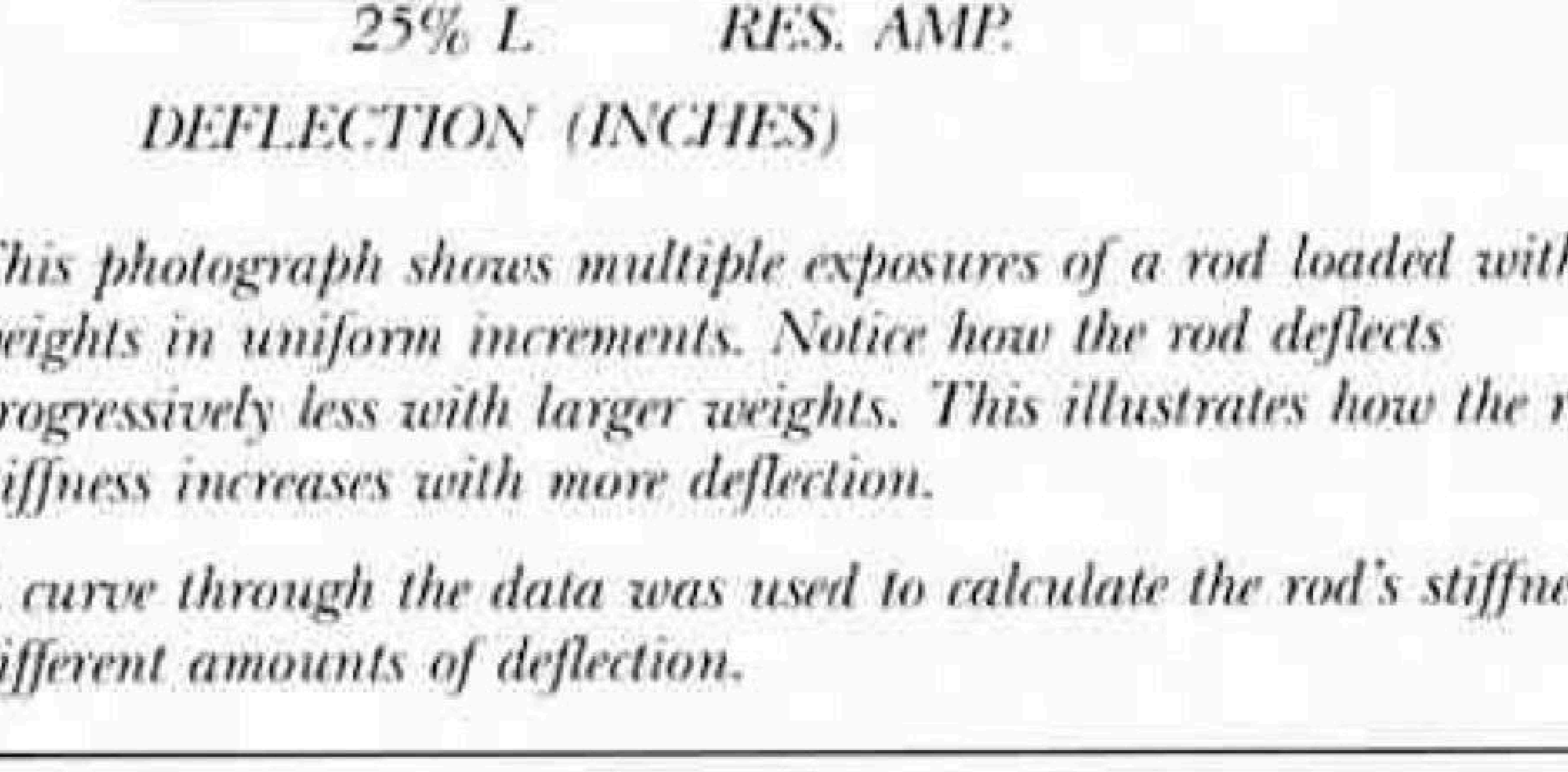


To measure rod stiffness, the rods were mounted in a special fixture. Weights were hung from the rod tip, and the bent rod was photographed. The rod tip deflection and the area swept during deflection were then measured.



Each rod was loaded with four different weights. This is a multiple-exposure photograph of a single rod with loads that increase in equal increments.





This photograph shows multiple exposures of a rod loaded with weights in uniform increments. Notice how the rod deflects progressively less with larger weights. This illustrates how the rod's stiffness increases with more deflection.

A curve through the data was used to calculate the rod's stiffness at different amounts of deflection.

length squared to yield normalized deflections. (The second method has greater technical validity, but is more complicated than is necessary for this study. Hence, it was not used for analysis.)

Since the rod's stiffness increases as greater loads are applied, four different loads were applied to each rod. The amount of load for each rod was based on the individual rod masses. The applied loads were one, two, three, and four times the rod mass. Multiple-exposure photography was then used to record on a single picture the rod deflections for the four loads (see photograph).

Frequency

Measuring the natural frequency of a fly rod is more complicated than one might initially suppose. Some factors to be considered are:

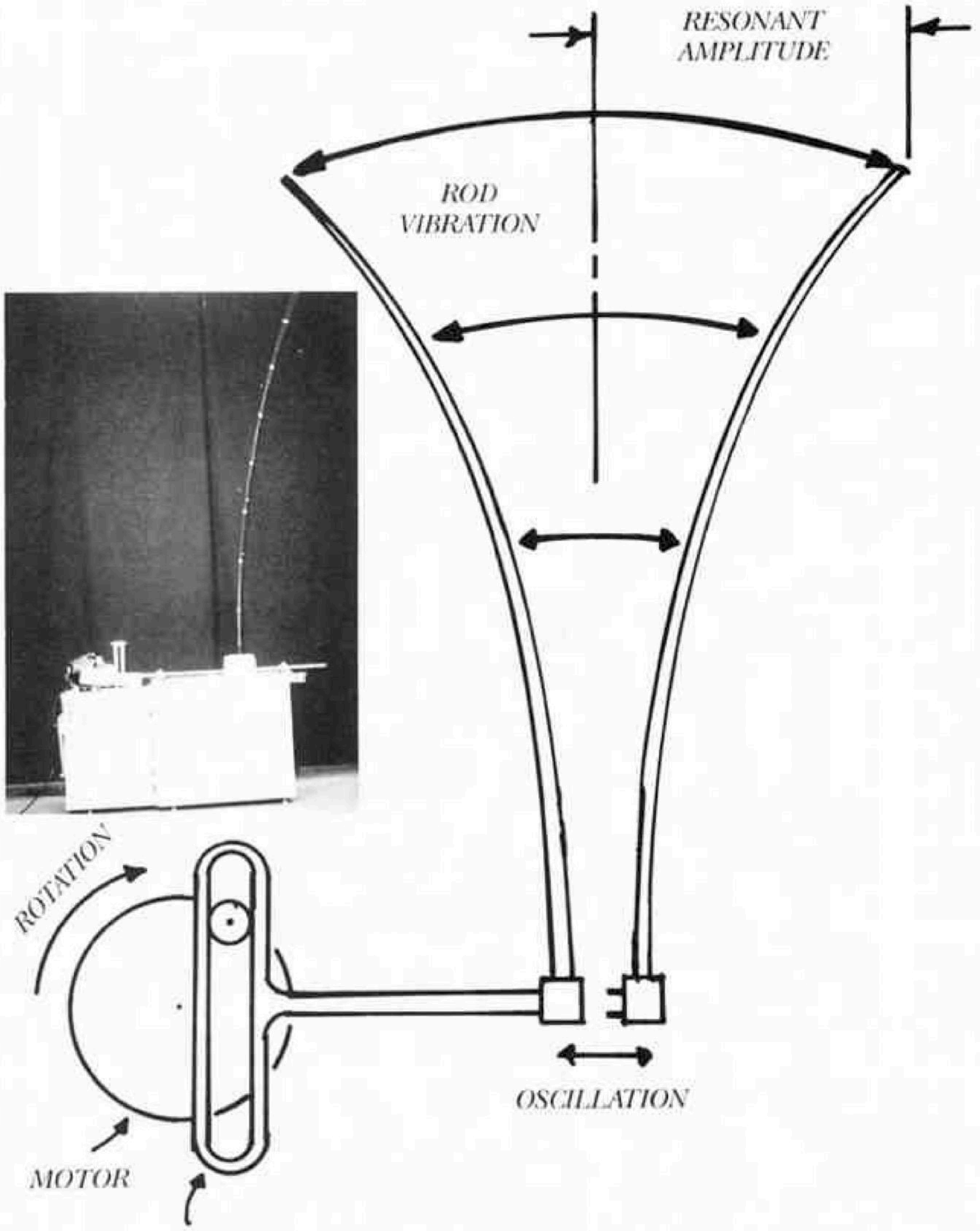
1. There are actually an infinite number of natural frequencies at which a fly rod will vibrate. All of them cannot be measured. Fortunately, the lowest, or fundamental, frequency is the most important one for casting; this was the one measured.
2. A rod's frequency depends on how the rod is held at the butt. We often see someone wriggle the butt of a rod and examine the rod's pattern of oscillation. But wriggling the butt back and forth is not the casting motion, so it does not test the rod as it would actually be used. A more representative butt motion is cantilever motion, whereby the butt is moved back and forth but not allowed to rotate. Because this motion is very difficult to perform manually, I used a machine for this purpose.
3. A rod's motion, whether during casting or vibration testing, is very strongly affected by air drag. If air drag were mathematically simple, one could "pluck" a fly rod like a guitar string and then count the frequency of the vibrations as they died out. But, of course, air drag is not simple, so one must measure the rod frequency as the rod is forced to vibrate in a repeatable pattern. A rod-shaking machine with repeatable motion was required.
4. A rod vibrates differently if it is moved with differing motions. The input motion that most exactly matches the rod's motion, thereby giving the best measure of rod vibration, is a sinusoidal motion. Sinusoidal motion is very easy to describe mathematically and very difficult to produce mechanically. The rod-shaking machine *(vide ante)* was developed to generate this motion.

After much design time, testing, and redesign, a rod-shaking machine to deliver the required motion was finally developed. For this apparatus (see illustration), the rod was mounted vertically and clamped at its butt so that the butt could not rotate. The butt was moved back and forth horizontally with pure sinusoidal motion. That motion was generted by a motor that ran at a constant speed and by a Scotch yoke that converted rotary motion into translational motion. The input vibration frequency for the rod was controlled by changing the motor speed.

During a test, the rod was securely mounted in the clamp, then the motor was turned on at low speed. The motor speed was stepped up sequentially to cause the rod to be shaken at higher frequency. At each step, the amplitude of the rod-tip motion was observed. When the shaking frequency matched the rod's natural frequency, the rod-tip motion had its greatest amplitude; subsequent increases in the motor speed caused a decrease in rod-tip amplitude. When the rod was vibrating at its natural frequency, the resonant frequency was measured with an oscilloscope, and a screen was moved into position so that the rod tip just touched it during its vibration. The machine was then shut down, and the distance between the screen and the rod at midstroke was measured; this distance was the resonant amplitude.

Results

From the rod data obtained (see summary of results), it is obvious that the fly rods tested exhibited a wide range of traits. While the sampling of rods is not exhaustive, a wide range of rod materials was examined: lancewood, greenheart, Calcutta cane, Tonkin cane, fiberglass, and graphite. The date or era assigned to each of these materials is only approximate, for they were likely used before and certainly used after the date given. The purpose of the date is to place the use of each material in historical perspective so that the chronology of the evolution, if there is one, can be identified.



A rod-shaking machine was built to measure the rod frequency. The rod was clamped at its handle and moved back and forth with a Scotch yoke mechanism. The amount of rod vibration was greatest at resonance.

For the most part, all of the rods tested were of comparable length. The average length was approximately nine feet (a range of eight to ten feet).

The weights of the rods (overall mass) vary considerably, the newer graphite rods weigh about 80 grams, while the comparable lancewood or early bamboo rods weigh more than 200 grams, or 2.5 times as much! Two of the rods weighed 300 grams, but these were salmon rods that would be expected to be more massive.

The diameters of the rods also show a great deal of variability. The graphite rods have butt diameters in the range of .25 to .30 inches; the bamboo rod butt diameters range from .35 to .45 inches; and the hardwood rods have diameters in the range of .50 to .80 inches. Since the stiffness of the rod varies inversely with diameter raised to the fourth power (see part one of this series), it is easy to see that the graphite rod with a diameter half that of a lancewood rod must use a material with about sixteen times the modulus. Or, put another way, rod designers had to find a material with sixteen times the inherent stiffness just to reduce the diameter by a factor of two. With this perspective, we can begin to understand the limitations that face future rod development.

Besides the differences in butt diameters of fly rods, their tapers vary considerably. For each of the rods tested, the rod taper has been plotted on a common scale. It is clear that the tapers for graphite rods are very straight and uniform, while the tapers for some of the hardwood and bamboo rods are quite erratic. This inconsistancy can, in part, be attributed to the three-piece construction and the abrupt diameter changes at the ferrules that are common in these older wooden rods. It should be noted that the taper variations plotted for the hardwood and bamboo rods tested are probably unique to these rods, and if different rods were tested, different tapers would have been measured. Hence, these rods probably exhibited vastly different casting and flexing behavior when fished, and their performance could not be anticipated until use. In this respect, our modern glass, graphite, and boron rods offer far more predictability in field performance.

Before we can compare the stiffness of rods, we must carefully define the stiffness we are comparing. As has been emphasized throughout, the stiffness of a rod depends on how much deflection the rod experiences. This effect becomes most apparent when we look at the patterns of deflection for prograssively increased load (see accompanying photograph). When loading is increased in uniform steps, the rod deflects less and less, which indicates a correspondingly increased stiffness. If we plot the deflection vs. load (see illustration) for a rod and obtain a smooth curve through those data points, the slope of that curve represents the stiffness of the rod. As the slope increases progressively, so does the stiffness. This procedure—plotting the curve and finding the slope—was performed for all rods tested. The slope was then calculated at two different tip deflections: (1) when the rod tip deflected twenty-five percent of the rod length (25% L), and (2) when the rod tip deflected the amount measured at resonant vibration (Res. Amp.). Of these two, the former proved to be a more consistent indicator of rod stiffness and was used for comparisons.

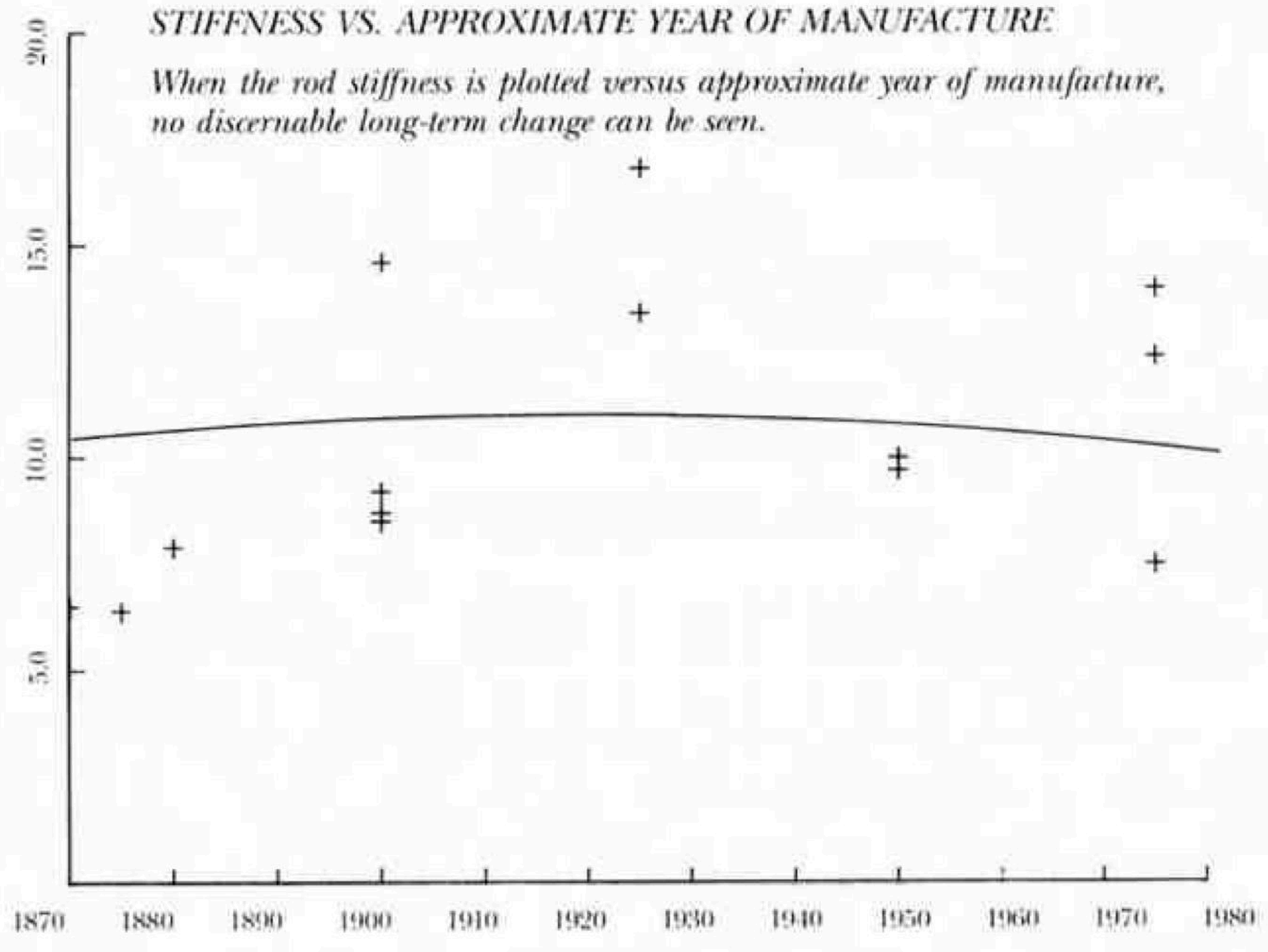
Let us now compare rod stiffness. Excluding the two salmon rods (rod no. 7 and rod no. 13), the stiffness of all rods was in the range of .0064 to .0168 pounds per inch. When we plot the change of this stiffness with the year of manufacture (see illustration), no progression is apparent. The data is widely scattered because of the differences in the rods, but a curve representing all of the data is basically flat. We must conclude that the rod stiffness has not changed dramatically, but rather has remained essentially constant with the passage of time.

Next, examine the changes in rod frequency. The rod frequency is somewhat easier to define than stiffness because it does not change with deflection (actually is changes slightly, but we will ignore that effect for simplicity). The frequency is expressed as the number of oscillations that the rod undergoes per second, or cycles per second. For the rods tested, the frequency varies from 1.2 to 2.6 cycles per second. When we plot the change of the frequency with time (see illustration), the progression is immediately obvious. The low-frequency rods of a hundred years ago have been replaced by the high-frequency rods of today. The curve representing the data shows this increase clearly. The curve also seems to show that the frequency increase has been slowing down recently. Being careful to not read too much into this small amount of data, I am tempted to interpret this slowing down effect as our approach to the technical limit of currently available materials. While it is possible to build a higher frequency rod with modern materials, we must keep in mind that it

SUMMARY OF RESULTS

Rod Manufacturer	*Rod Number*	*Material*	*Technology date**	*Overall length (inches)*	*Length w/o grip (inches)*	*Overall mass (grams)*	*Mass w/o grip (grams)*	*Balance (inches)*	*Stiffness-25%*	*Stiff. res.*	*Frequency*
Lamiglas	*1*	*graphite*	*1975*	*96.0*	*88.0*	*83.0*	*35.3*	*101.5*	*0.0075*	*0.0132*	*2.47*
Unknown	*2*	*fiberglass*	*1950*	*75.0*	*65.0*	*84.5*	*27.6*	*31.0*	*0.0097*	*0.0190*	*2.57*
J. S. Sharpe *orig. wooden rod*	*3*	*Tonkin cane, impreg.*	*1950*	*90.5*	*81.5*	*113.5*	*79.0*	*213.5*	*0.0134*	*0.0259*	*2.44*
Shakespeare	*4*	*fiberglass*	*1950*	*93.0*	*82.5*	*105.7*	*66.0*	*128.0*	*0.0100*	*0.0250*	*2.62*
Orvis	*5*	*Calcutta cane*	*1875*	*131.5*	*119.5*	*204.0*	*114.0*	*312.0*	*0.0064*	*0.0194*	*1.22*
Forrest and Sons	*6*	*greenheart*	*1880*	*127.0*	*117.5*	*205.7*	*159.0*	*547.0*	*0.0079*	*0.0251*	*1.37*
Vom Hofe (?)	*7*	*greenheart*	*1880*	*105.5*	*92.0*	*298.3*	*204.0*	*356.0*	*0.0266*	*0.0701*	*2.00*
Silkien	*8*	*cane*	*1900*	*109.0*	*99.5*	*144.0*	*97.0*	*300.0*	*0.0085*	*0.0257*	*1.49*
Chubb	*9*	*lancewood*	*1870*	*120.5*	*109.0*	*207.0*	*117.0*	*297.0*	*0.0065*	*0.0288*	*1.18*
Orvis	*10*	*cane*	*1900*	*108.0*	*97.0*	*153.0*	*88.0*	*216.0*	*0.0087*	*0.0268*	*1.43*
H. L. Leonard	*11*	*Tonkin cane*	*1900*	*114.0*	*104.0*	*173.0*	*81.0*	*214.0*	*0.0146*	*0.0260*	*1.77*
Abbey and Imbrie	*12*	*cane*	*1900*	*118.0*	*105.0*	*227.5*	*114.0*	*227.0*	*0.0092*	*0.0277*	*1.58*
Abbey and Imbrie	*13*	*lancewood*	*1870*	*104.0*	*90.5*	*324.5*	*184.9*	*301.0*	*0.0298*	*0.0694*	*2.38*
Orvis	*14*	*graphite*	*1975*	*107.5*	*97.5*	*86.0*	*53.5*	*150.0*	*0.0124*	*0.0186*	*2.41*
Shakespeare	*15*	*graphite*	*1975*	*107.5*	*94.0*	*146.0*	*67.9*	*113.0*	*0.0140*	*0.0207*	*2.60*
Orvis	*16*	*cane, impreg.*	*1950*	*112.0*	*101.0*	*211.0*	*132.5*	*359.0*	*0.0168*	*0.0422*	*1.96*

**These dates were supplied by the author. The rods were loaned by the Museum to the author for testing. Unfortunately, the dates of manufacture of the rods are not known precisely. The author has estimated the date when the particular rod technology was developed, and these dates are not really accurate. The older rods are circa 1900 or before. The lack of precision in assigning dates in no way detracts from the author's arguments.*



STIFFNESS VS. APPROXIMATE YEAR OF MANUFACTURE

When the rod stiffness is plotted versus approximate year of manufacture, no discernable long-term change can be seen.

must still retain the stiffness and weight features necessary for effective fishing. Thus, we may be approaching the practical limit to rod frequency and increased line speed.

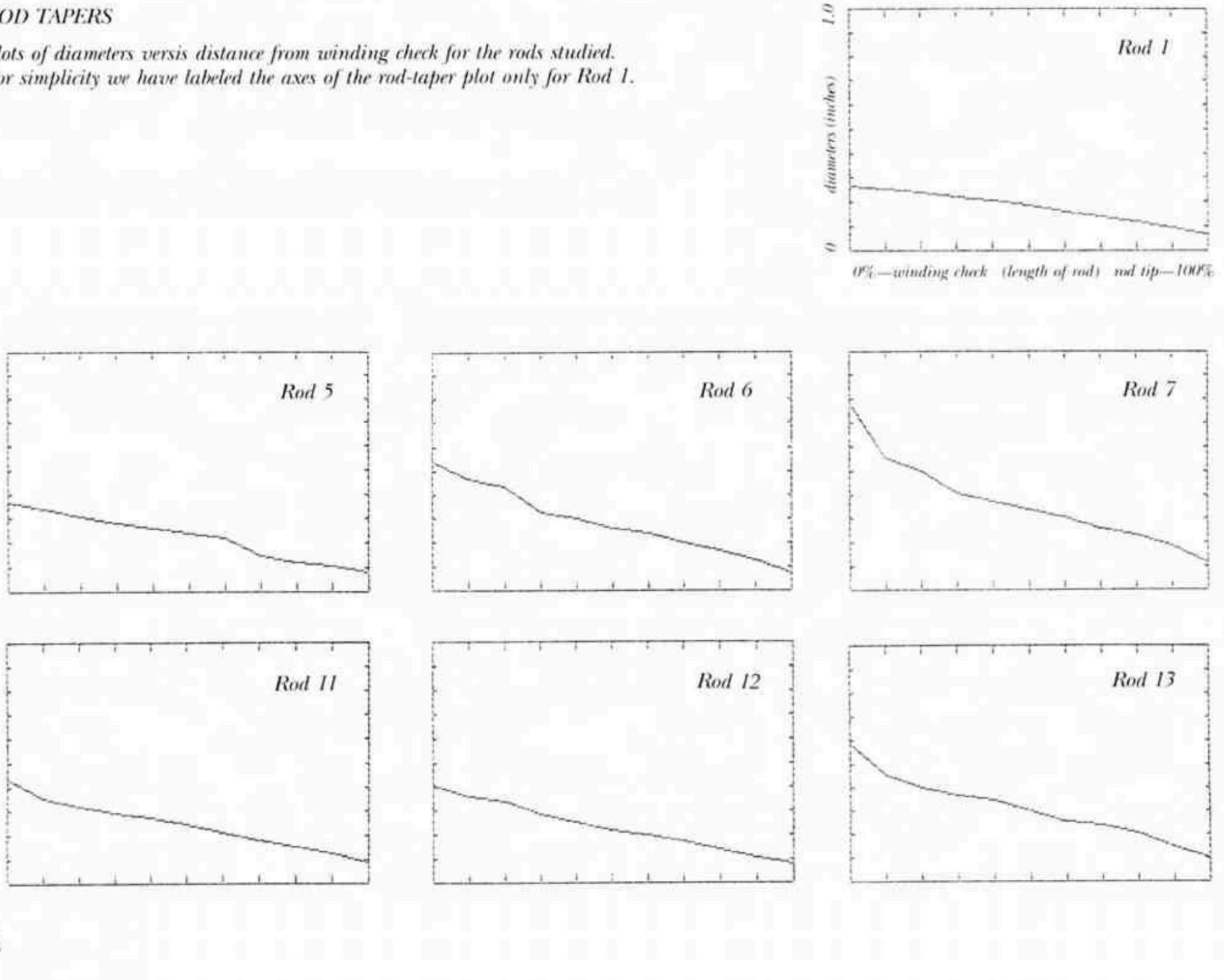
Conclusion

So what have we discovered about the evolution of fly rods? First, I think that it is clear that rod stiffness has not changed very much, while rod frequency has increased dramatically. In our fly-fishing efforts, this translates into easier casting. Furthermore, it appears that we are approaching a limit to increased frequency or improved casting with the rod materials currently available. Any improvements that we can reasonably expect in the near future will probably be small compared to the giant steps taken when fiberglass and graphite first appeared.

And now that we have a better understanding of the factors that affect fly-rod performance, perhaps we can now con-

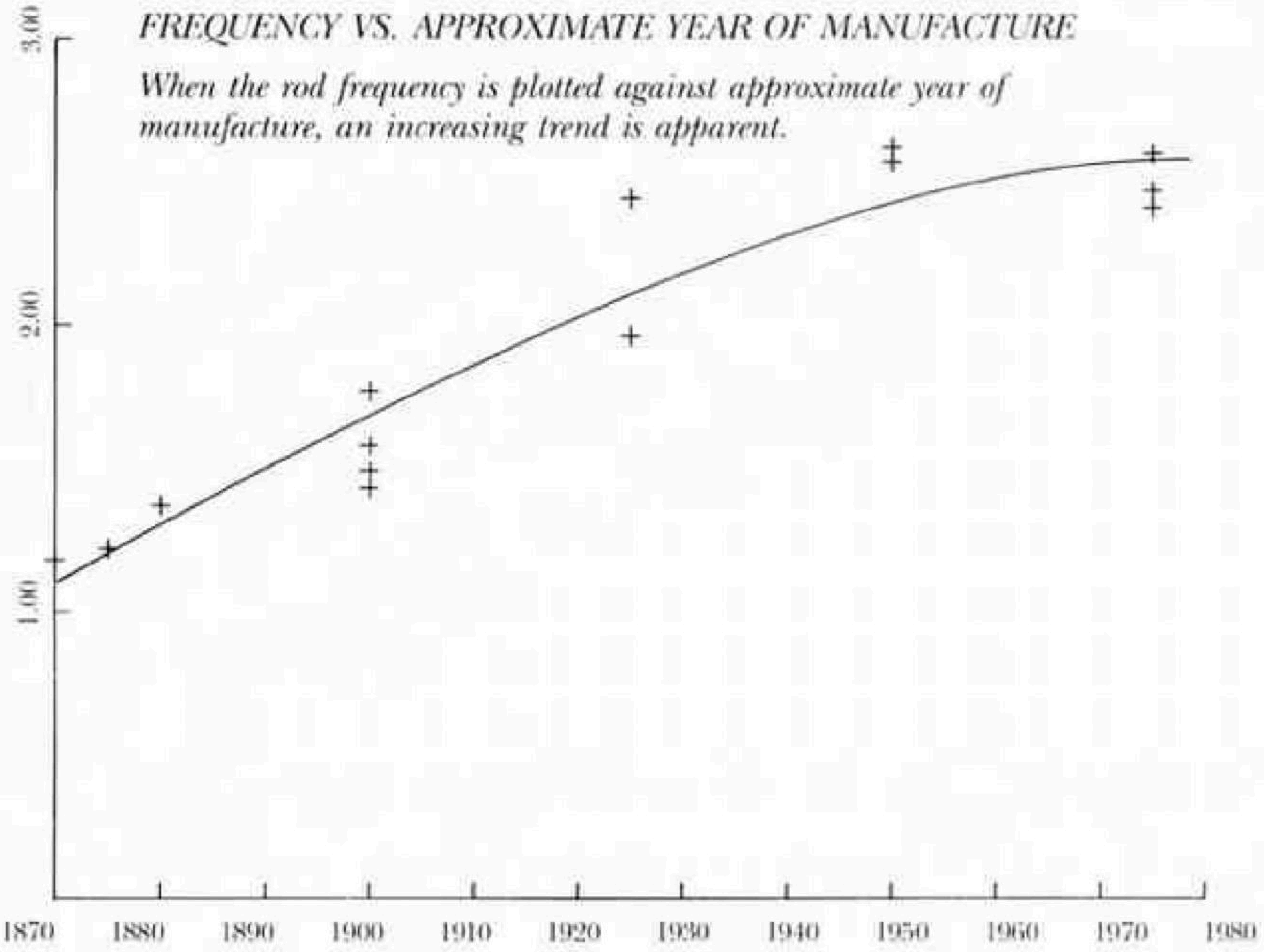
ROD TAPERS

Plots of diameters versis distance from winding check for the rods studied. For simplicity we have labeled the axes of the rod-taper plot only for Rod 1.



sider a quantitative method for rating fly rods. Currently, rod ratings are very subjective. They indicate the line weight that the rod casts best, as determined by a panel of expert casters. This rating includes some aspects of both the stiffness and frequency of the rod. Furthermore, the current system is inaccurate because as we have demonstrated, the rod's stiffness and frequency are separate and independent. No single rating value can accurately represent both factors.

A new rating method is therefore needed for fly rods. It must include an indicator for *both* stiffness and frequency. Thus, two rating values, rather than one, must be employed. A numerical system that uses, for example, a 1 to 10 scale for stiffness and a 1 to 10 scale for frequency (much the same that we currently use a 1 to 10 scale for line weights) would suffice. It would take us a while to get used to the system; but once we had taken this step we would have in hand an accurate, quantitative method for a priori assessing the way a fly rod will perform in the field. §



FREQUENCY VS. APPROXIMATE YEAR OF MANUFACTURE

When the rod frequency is plotted against approximate year of manufacture, an increasing trend is apparent.