VIBRATION INDUCED YAGI FATIGUE FAILURES

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Yagi element failure can be attributed to two basic causes. The first type of failure occurs when an element isn't strong enough to hold up when forces are applied. These forces may be caused by a thick layer of ice, high winds, or a combination of the two. Under the stress of these forces, the element either bends or breaks off, with signs of bending in the area of the break.

The second type of failure takes place after an element has been fluttering, or vibrating, in a relatively low wind stream. The break caused by this kind of failure is quite different. There's no sign of bending in the area of the break; it's a jagged line through the element. In addition to element fluttering, boom fluttering (although not as common) can lead to the same failure.

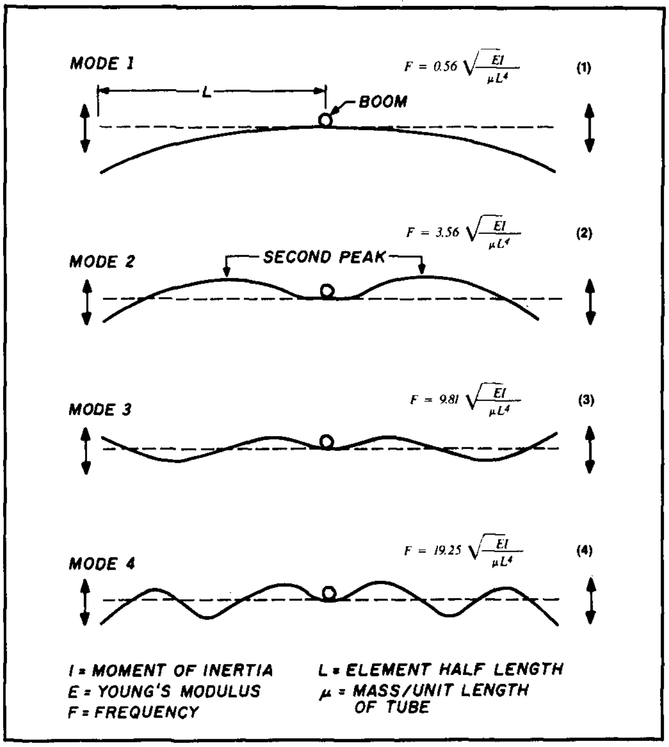
Because there's no sign of bending you'll know that the stress levels in the material are relatively low, yet failure occurs. What causes an element to flutter in the wind? What causes a break although the stress levels are well below those required to bend the tube? And what methods will minimize or eliminate this type of failure?

Understanding flutter

Two key areas that must be explored to understand flutter are the vibratory aspects of the element and the forces that set it in motion.

An element has mechanical resonant frequencies which can be excited. **Figure 1** shows four modes of element vibration and the shape the element takes during oscillation in each mode. These resonant modes happen at discrete, not harmonically related, resonant frequencies. The element has stiffness and mass — the necessary ingredients for resonance. The modes are different situations where the ingredients blend properly to yield resonance. There's a separate resonant frequency with each mode. This means the element can have several resonant frequencies. Use the equations shown with each mode in **Figure 1** to calculate the resonant frequency for that mode. **Equations 1** through **4** are for an element made of one tubing size.[1] Finding resonant frequencies for elements constructed of telescoped sections is best handled by computer finite element structural analysis programs. You can make approximations with the equations shown by selecting a tube diameter the same as the second or third smallest in the element. **Table 1** shows the resonant frequencies for various lengths and sizes of tubing for the first four modes. (Telescoped elements will have resonant frequencies in the ranges shown in **Table 1**.)

FIGURE 1



The four possible modes of element oscillation.

The mechanical resonances are lightly damped. Their behavior is exactly like high Q resonant electrical circuits. As a result, small exciting forces cause large displacement oscillations. For this to happen, and for flutter to be established, there has to be an exciting force at or very near one of the mode resonant frequencies. In addition, the excitation must be maintained to sustain the element oscillation. Where does this excitation come from? How can a mild wind stream provide a vibratory input to initiate and maintain an element oscillation?

Wind excitation

Several things can occur when air flows over a round tube. At low wind speeds nothing happens. The air flows around the tube creating no disturbances of any kind. At higher wind speeds, the air can't cling to the back side of the tube. This creates vortices, or swirls of air. At first the vortices form in pairs coming from both edges of the tube.

TABLE 1

Resonant frequencies of the first four modes for various element configurations.

Element Tube Diameter (inches)	Half Length (inches)	Wall Thickness (inches)	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)	Mode 4 (Hz)
0.500	100	0.058	1.2	7.9	21.8	42.6
0.625	100	0.058	1.6	10.0	27.8	54.5
0.750	100	0.058	1.9	12.3	33.8	66.4
0.875	100	0.058	2.3	14.5	39.9	78.3
0.500	135	0.058	0.7	4.3	11.9	23.4
0.625	135	0.058	0.9	5.5	15.2	29.3
0.750	135	0.058	1.1	6.7	18.6	36.4
0.875	135	0.058	1.2	7.9	21.9	42.9
1.000	135	0.058	1.4	9.2	25.3	49.5
0.625	200	0.058	0.4	2.5	6.9	13.6
0.625	200	0.116	0.36	2.3	6.4	12.5
0.750	200	0.058	0.5	3.1	8.5	16.6
0.750	200	0.116	0.45	2.9	7.9	15.4
0.875	200	0.058	0.6	3.6	10.0	19.6
0.875	200	0.116	0.5	3.4	9.4	18.3
1.000	200	0.058	0.7	4.2	11.5	22.5
1.000	200	0.116	0.6	3.9	10.6	21.3
1.125	200	0.058	0.75	4.7	13.0	25.5
1.125	200	0.116	0.7	4.5	12.4	24.3
1.250	200	0.058	0.83	5.3	14.5	28.2
1.250	200	0.116	0.79	5.0	13.9	27.2

FIGURE 2

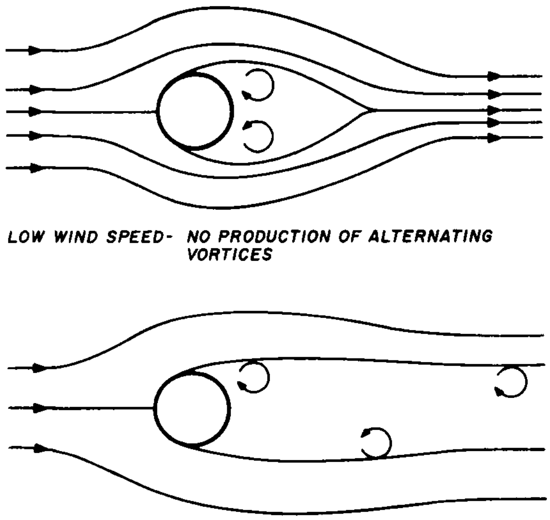


Diagram showing the cause of oscillation due to the creation of alternating vortices.

As the wind speed increases, the vortices leave first one edge of the tube and then the other. The formation of the vortices alternates back and forth between the two edges. The result is an oscillatory pressure loading on the tube. When the frequency of vortex formation is the same as the resonant frequency of one of the element vibratory modes, the element begins to flutter. **Figure 2** shows the various stages of vortex shedding.

As the wind stream velocity increases, the frequency of vortex formation accelerates. When the frequency of the vortex shedding builds up sufficiently, the element stops vibrating because the excitation is not at, or near, a mode resonant frequency. Similarly, as the wind speed decreases, either vortices cannot be shed or the frequency of shedding drops below a mode resonant frequency. The result is the same: the element stops vibrating.

As the wind speed continues to increase, vortices continue to be produced, but with greatly diminished amplitude. No effective excitation is produced above a certain air velocity. The result is a range of possible frequencies that can excite an element. The element will flutter only if the wind sheds vortices from the tube at or near an element mode resonant frequency.

Use **Equation 5** to find the shedding frequency.[2] The term Nr is an important parameter; it determines the interplay of the tube size, air velocity, air density, and air viscosity. Shedding occurs when Nr is in the range of 60 to 10,000.[3] Although shedding can occur over this wide range of Nr, other conditions may not be suitable for the initiation of element flutter.

$$f = 3.52 \cdot \frac{V}{D} \cdot \left[1 - \frac{20}{Nr}\right] \qquad \textbf{(5)}$$

$$Nr = 774 \cdot V \cdot D \qquad \textbf{(6)}$$

f = frequency of vortex shedding (Hz)
V = wind velocity (mile/hour)
D = tube diameter (inches)
Nr = Reynolds number (dimensionless) (air parameters factored into coefficient)

TABLE 2

Wind and frequency ranges for vortex shedding

Tube size (inches)	Wind speed range (mph)	Frequency range (Hz)
0.250	0.30—52	2.8—730
0.375	0.20—34	1.4—318
0.500	0.16—26	0.8—182
0.625	0.13—21	0.5—118
0.750	0.10—17	0.3—80
0.875	0.09—15	0.2—60
1.000	0.08—13	<0.2—46
1.125	0.07—11	<0.1—34
1.250	0.06—10	<1.1—28

Table 2 shows the wind speed ranges for tube sizes having the correct Nr range. There's no reason to consider wind speeds out of these ranges for a particular tube size when using **Equation 5**. This means that for the tubing sizes used in a Yagi element there's an upper and lower boundary to the frequencies which may start fluttering. If an element is made of several diameters of tubing, the upper and lower shedding frequencies are determined by the smallest and largest diameter tubes, respectively. **Table 2** also lists the range of shedding frequencies for each tube size. The possible frequency range is, theoretically, extremely wide.

The extremely low wind velocities within the range of Nr offer little danger. There's generally insufficient energy in the wind stream to cause pressure loadings of any appreciable magnitude on the tube. In addition, at higher wind speeds the flow is so turbulent that the vortices don't all shed from one side of the tube and then the other. They come off the tube at about the same frequency, but not in an orderly fashion.[3]

What then is the proper range of wind speeds which can cause fluttering? My own experience and observations have been of wind speeds less than 35 mph. This still leaves a wide range of frequencies that can be generated by vortex shedding. I've seen many elements vibrate in mode 2 and several vibrate in mode 3. I've also seen elements vibrate at a fixed frequency even though the wind speed wasn't constant. This indicates that a broad band of frequencies can be generated by vortex shedding from the same element, not only because of multiple element diameters, but also because the shedding frequency isn't inherently stable. I have never seen mode 1. Either there's insufficient energy in the wind stream at these wind speeds, or the vortices detach themselves when the element begins to vibrate, and the element shuts itself down.

The possible range of exciting frequencies in **Table 2** shows that these frequencies are in the range of the resonant frequencies of the various tube configurations in **Table 1**. Don't consider the lower frequencies in **Table 2** too seriously; there's a very small level of energy in the corresponding wind streams. It also appears that elements should begin vibrating in any wind stream. In reality, this doesn't happen. Even in view of the anomalies, you can gain insight into the vibratory behavior of a fluttering element.

Element fatigue failure

An element that breaks as a result of sustained fluttering fails by a different mechanism than if it bends due to a very high force. When an element bends or breaks off because of a very high wind or ice load, the yield stress of the material has been exceeded. An element can be deformed by a force below the yield stress, but when the force is removed the element will return to its original starting point. For example, if you pull a Yagi element with your hand, it will deflect several inches. When you let go, the element will return to its original shape. If you pull on the element enough to give it a permanent bend, you have stressed the material above its yield stress. Therefore, exceeding the yield stress results in a permanent bend. If the yield stress is greatly exceeded, the element will first bend and then break. An element which fails due to fluttering breaks for a different reason.

When aluminum is flexed at levels below the yield stress, no permanent bend results but damage accumulates. If the flexing is repeated enough times, the accumulated damage in the material results in a fatigue failure. The higher the load, the less load applications are needed to give a fatigue failure. The lower the load, the more cycles of application are needed to create the same accumulated damage. When an element flutters long enough, the accumulated damage in the material gets to the level where the element suffers fatigue failure.[4] However, there's no sign of a bend or evidence indicating the material has exceeded its yield stress near the break.

Minimizing element failure

There are several things that can be done if an element flutters. You can attempt a modification to the element to limit the amplitude of the stress during fluttering. Try increasing damping in the element to extend its life. This will lower the Q of the mechanical resonance, which means that the tube will take many more load cycles to generate a failure. I've heard of people filling the inside of elements with foam intended for sealing and insulating cracks and holes in buildings. This method may work. But if you attempt this, take two identical elements and foam only one. After the foam has cured, shake both of them in your hand to see if there is an appreciable difference in how the element vibrates when excited. Shake the element to set up a mode 2 oscillation (see **Figure 1**). Once you have oscillation, stop moving your hand and see how long it takes for the element to stop shaking. If the foamed one damps out sooner, you may have a working solution.

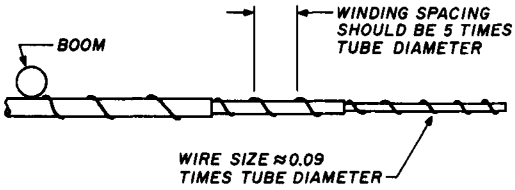
You might also modify the shape of the element so that orderly vortices can't be shed. To do so, wrap a wire in a helix around the element.[5] The wire diameter should be

TABLE 3

Resonant frequencies of the first four modes with 1/2″ rope for various element configurations

Tube diameter (inches)	Element half length (inches)	Wall thickness (inches)	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)	Mode 4 (Hz)
0.500	100	0.058	1.15	7.3	20.1	39.5
0.625	100	0.058	1.5	9.5	26.1	51.3
0.750	100	0.058	1.8	11.7	32.2	63.1
0.875	100	0.058	2.2	13.9	38.2	74.9
0.500	135	0.058	0.6	4.0	11.0	21.6
0.625	135	0.058	0.8	5.2	14.3	28.1
0.750	135	0.058	1.0	6.4	17.6	34.6
0.875	135	0.058	1.19	7.6	20.9	41.1
1.000	135	0.058	1.38	8.8	24.3	47.7
0.625	200	0.058	0.37	2.4	6.5	12.8
0.625	200	0.116	0.35	2.2	6.1	12.0
0.750	200	0.058	0.45	2.9	8.0	15.7
0.750	200	0.116	0.43	2.8	7.6	14.9
0.875	200	0.058	0.5	3.5	9.6	18.7
0.875	200	0.116	0.5	3.3	9.1	17.9
1.000	200	0.058	0.63	4.0	11.0	21.7
1.000	200	0.116	0.59	3.86	10.58	20.8
1.125	200	0.058	0.71	4.6	12.6	24.7
1.125	200	0.116	0.69	4.4	12.2	23.8
1.250	200	0.058	0.80	5.1	14.1	27.7
1.250	200	0.116	0.77	4.9	13.7	26.8

FIGURE 3



Experimental method for eliminating the creation of vortices by wrapping the elements with wire.

about 0.09 times the diameter of the element with the turns of the helix spaced about 5 times the diameter. (See **Figure 3**.) I don't know if anyone has tried this approach. I plan to experiment with it and I hope others will too. It offers the possibility of being the best solution. Rather than trying to accommodate the production of vortices, this approach may eliminate their generation. I know this idea has been applied successfully to various types of structures, like suspended pipelines and smoke stacks, but I'm not aware of its use with Yagi elements.

You can attempt to retune the mechanical resonances of the element out of the range of vortex shedding frequencies in two ways. One traditional method is to use damping ropes inside the elements. Actually, damping ropes provide both a slight mechanical retuning of the element and the addition of some amount of damping to lower the Q of the mechanical resonance. My experience with damping ropes has shown them to be of little value. I had four fatigue failures on a 20-meter Yagi and three on a 10-meter Yagi in one year. All had ropes. After the first break on each, I changed the ropes to the largest possible size, with no success.

The amount of mechanical retuning that results from placing a rope inside an element is shown in **Table 3**. I've calculated the resonant frequencies with a 1/2-inch rope inside the entire element length. A comparison of **Table 1** and **Table 3** shows the resonant frequencies haven't been substantially altered. If anyone has had success with ropes, it probably has been due to a lowering of the Q of the mechanical resonance by providing some damping. This was probably a marginal case. Evaluate this method the same way you did the foamed elements. Perhaps you can enhance the damping provided by the rope by gluing its entire length to the inside of the element. You'll probably have to soak the rope in an adhesive and coat the inside of the element before pulling the rope through.

A weight fastened to the tip of an element can alter the resonant frequency appreciably. **Table 4** shows the same element configurations, with a 3-ounce weight at the element tip. This table compares the first mode with and without the weight. There has been about a 40-percent reduction in resonant frequency. The second mode resonant frequency will be reduced further, while the higher modes' resonant frequencies will increase. I tested this on a 20-meter Yagi element and found that adding a 3-ounce weight cut the second mode frequency in half. The degree of retuning depends on element configuration and weight size.

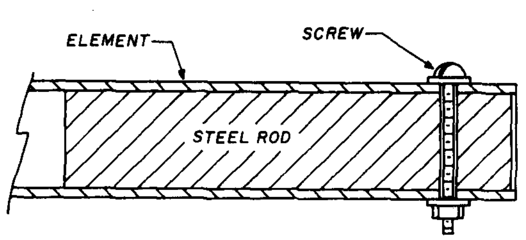
Several years ago Dennis Peters, N5UA (now deceased), had a 10-meter beam which was losing an element about every two months even though he had ropes in the elements. After some discussion and much frustration on his part, he added weights to each element tip. Dennis used large washers secured with hose clamps; they did the trick.

TABLE 4

Resonant frequencies of mode 1 without and with a 3-ounce tip weight.

Tube diameter (inches)	Element half length (inches)	Wall thickness (inches)	Mode 1, no tip weight (Hz)	Mode 1, with tip weight (Hz)
0.500	100	0.058	1.2	0.7
0.625	100	0.058	1.6	1.0
0.750	100	0.058	1.9	1.27
0.875	100	0.058	2.3	1.51
0.500	135	0.058	0.7	0.44
0.625	135	0.058	0.9	0.57
0.750	135	0.058	1.1	0.70
0.875	135	0.058	1.2	0.84
1.000	135	0.058	1.4	0.97
0.625	200	0.058	0.4	0.27
0.625	200	0.116	0.36	0.25
0.750	200	0.058	0.5	0.33
0.750	200	0.116	0.45	0.31
0.875	200	0.058	0.6	0.39
0.875	200	0.116	0.5	0.37
1.000	200	0.058	0.7	0.45
1.000	200	0.116	0.6	0.43
1.125	200	0.058	0.75	0.51
1.125	200	0.116	0.7	0.49
1.250	200	0.058	0.83	0.57
1.250	200	0.116	0.79	0.55

FIGURE 4



Adding weight to reduce the mechanical resonant frequency.

The antenna suffered no failures in the year before his station was dismantled.

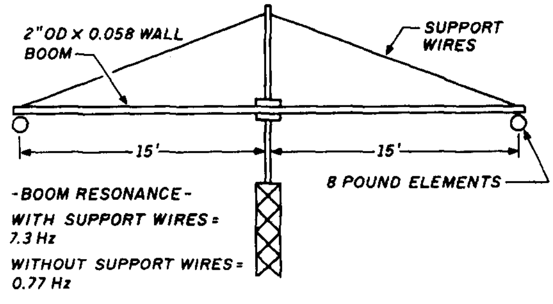
Add weights by clamping them to the outside of the element or securing them to the inside. You can slip lengths of steel rod into the tip of an element and secure them with screws. (**Figure 4** shows this method of attachment.) If you add weights, they can't be taped to the element. They must be hard mounted.

There are two preferred locations for adding weights. The first is at the tip. Another spot is about one-fifth of the way from the tip to the boom. The tip moves the most in modes 1 and 2; the second location moves substantially in mode 2. Adding weights loads these locations for the most dramatic retuning. Observe the shape the element takes when it's fluttering in order to determine weight placement. You'll see a displacement peak at the tip, and another part way to the boom. Put the second weight at the second peak. In **Figure 1**, the second peak is labeled for mode 2.

Boom flutter

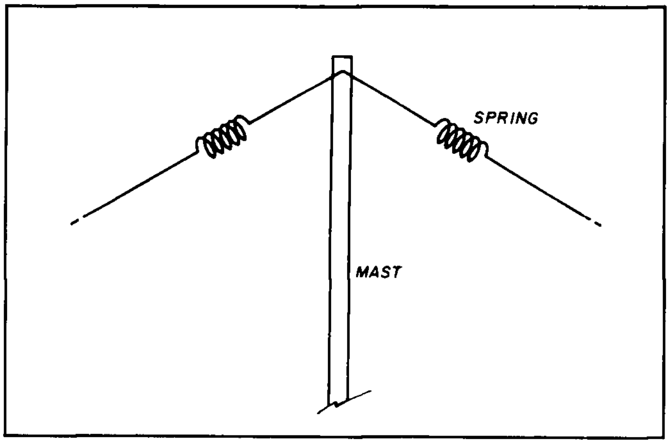
I've seen booms fluttering on several occasions. One boom eventually failed at the mast end. This failure isn't as common as element flutter, but it does happen. The cases I've observed have all had boom support wires strung from the mast to the boom. For the boom in **Figure 5**, the resonant frequency with the support wires is 7.3 Hz. Without the support wires, the resonant frequency is 0.77 Hz. Getting rid of the wire drops the resonant frequency substantially, but a lack of support wires may not be acceptable. Fortunately, there's an easy solution to the problem. The key is to provide the support needed, but not the stiffness of the support wire. Install a spring in the support wire as shown in **Figure 6**. The softer the spring the better. Pick a spring, or series of springs, that won't be stretched excessively by the tension needed to support the boom. This will

FIGURE 5



Case where boom with support is more prone to flutter.

FIGURE 6



Installing stiff springs in the boom support lines to damp the resonant frequency.

decouple the stiffness of the support wire and still provide the needed tension. The shift in resonant frequency will most likely put the boom into an area where either the energy in the wind stream isn't sufficient to start flutter, or the boom resonant frequency is below the vortex shedding minimum.

Element design variations

I've had Yagis with severe fluttering problems. I've also had Yagis with no problems at all. Those having failures were very stiff when compared with their mass, while those that had no damage weren't as stiff when compared with their mass. In **Equations 1** through **4**, the term $\frac{EI}{u}$ appears. EI is a stiffness term, and u is a mass term. The lower the "stiffness to mass" ratio, the lower the mode resonances. Based on the Yagis I have owned, I've concluded that elements with the lower resonant frequencies have the best chance of not fluttering. This suggests that retuning the element is indeed a viable approach, a fact supported by the experiences of Dennis Peters. I'd be very interested in hearing from any readers who have experienced problems with fluttering elements, whether you've been successful at solving them or not.

Summary

Elements and booms have mechanical resonant frequencies which can be put into oscillation by vortices shedding from the tube edges. There are several ways to reduce the likelihood of a fatigue failure. Damping can be added to reduce the amplitude of the stress. This would lengthen the life of the element. Adding damping ropes may help in marginal cases. Other methods have been tried, and there is certainly room for innovation. You can test an idea on the ground to see if it will reduce the Q of the mechanical resonance by noting the time it takes for oscillatory motion to damp out.

The most promising approach for minimizing element fatigue failures is to eliminate the orderly generation of vortices. The orderly formation of vortices will be disrupted in an element which is helically wound with a wire. To the best of my knowledge, this approach hasn't been tried with Yagis. It may prove to be the most effective remedy for fluttering elements.

There's a successful approach that's been used to eliminate element fatigue failures. Retuning the resonant frequencies of an element offers a means to prevent fatigue failure by moving the element resonances out of the shedding frequency range. You can do this by adding small weights. At minimum, the weights should be added at the element tips. A second location is on the span of the element, at the point with the largest displacement during a mode 2 oscillation. In addition, when selecting or designing a Yagi, keep in mind that elements which aren't very stiff in relation to their mass are less prone to vibration-induced fatigue failures.

Yagi booms are also subject to vortex shedding and fatigue failures. Booms with support wires have been observed to be most prone to fluttering. You can retune a boom with support wires by the adding springs in line with the wires. This lowers the resonant frequency of the boom and prevents it from fluttering. hr

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