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Determination of Yagi Wind Loads Using the "Cross-Flow Principle"

Find Yagi wind loads with this well-known method

I'd like to talk about a well-known and proven method of determining the wind loading on structural members. I've applied it here to a Yagi with horizontal elements to find the forces caused by wind loading. After defining and discussing the forces, I'll recommend a standard for comparing the wind loading of Yagis.

In the course of my work, I learned that the method currently used to define wind loads on Yagis is incorrect. Although this method has been used for over twenty-five years, it has gone unquestioned. Today, this incorrect method is used widely in the amateur radio antenna industry, and in amateur radio literature and software. I hope a simple standard based on sound, proven scientific methods will be adopted, and that these methods will be used throughout the amateur antenna industry. I hope the work presented here will help people become familiar with the concepts upon which the suggested standard is based.

L/D	C
0 – 4	0.7
>4 – 8	0.8
>8 – 40	1.0
>40	1.2

$L/D = \dfrac{\text{tube length}}{\text{tube diameter}}$

Table 1. Drag coefficient for round tube.

V (mph)	70.0	80.0	86.6	100.0
P (psf)	12.5	16.4	19.2	25.6

Table 2. Values of P at several values of wind velocity.

Forces Due to Wind

When an object—like an element or boom of a Yagi antenna—is in a wind stream, a force results when the wind strikes the object. The magnitude of the force depends on the velocity of the wind, the size of the object, the shape of the object, and the object's orientation relative to the wind stream. As the wind strikes an object, it creates a dynamic wind pressure that acts on the object's area. The higher the wind velocity, the higher the pressure. It's possible to calculate the dynamic wind pressure using **Equation 1.**

$$P = 0.5\ m\ V^2 \qquad \textbf{(1)}$$

where:

P = dynamic wind pressure
m = air mass density
V = air velocity

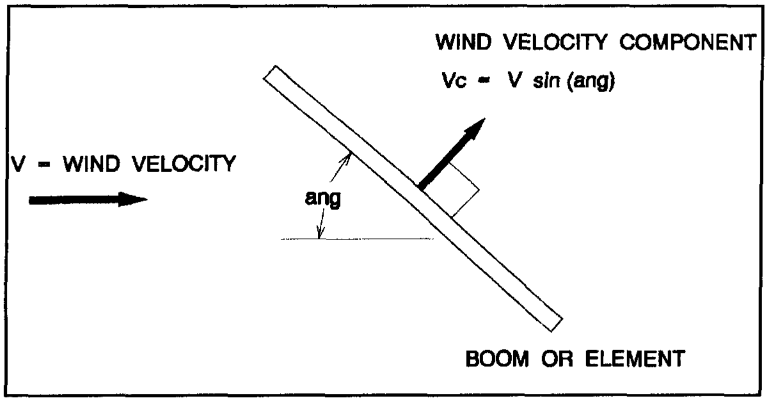


Figure 1. Wind velocity component as a function of angle.

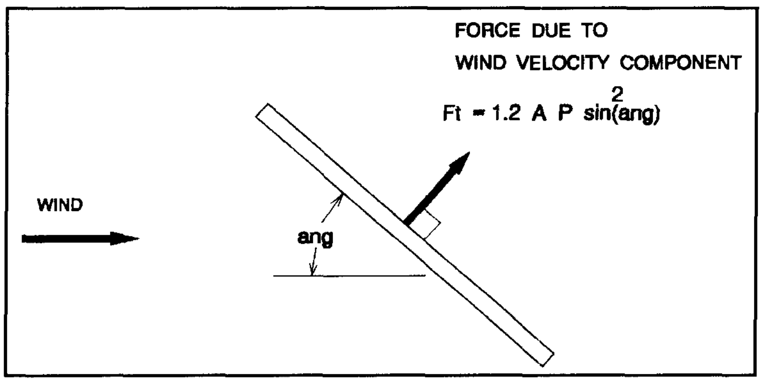


Figure 2. Force on round tube inclined to wind.

Equation 1 shows that the dynamic wind pressure depends on wind velocity and air mass density. To simplify matters, we use the density of air at "standard sea-level" With wind velocity in MPH and using "standard sea-level" air mass density, **Equation 1** is simplified to provide **Equation 2.**[1]

$$P = 0.00256\, V^2 \tag{2}$$

where:

P = dynamic wind pressure (psf)
V = wind velocity (MPH)

Now that we can determine the dynamic wind pressure, we need a relationship that accounts for the size and shape of the object.

Equation 3 gives this relationship for wind perpendicular to the object.

$$Fw = C\, A\, P \tag{3}$$

where:

Fw = force (lbs)
P = dynamic wind pressure (psf)
A = projected area (square feet)
C = drag coefficient (no units)

Consider the projected area of an object as the object's shadow or broadside area. For a round tube, we would find the projected area—multiplying the tube's diameter by its length. This tells us something about the tube size, but nothing about the object's streamlined nature. Enter a term called the drag coefficient. The lower the drag coefficient, the lower the force. For a round tube that's long compared to its diameter, C = 1.2.[2] For round tubes that aren't long compared to their length, C is less. There's a logical reason for this. Air only flows over the sides of an infinitely long tube, while shorter tubes experience flow over both the sides and the ends. With flow over the ends, there's less drag produced relative to the overall length of the tube. **Table 1** shows this effect. For HF Yagis, L/D is generally greater than 40. As a result, we'll use C = 1.2 for round tubes in this article. As a point of interest, a flat plate which has C = 2.0 is a common shape used for mounting plates and brackets.[2]

Clarification of Wind Pressures

Table 2 gives values of P at several levels of wind velocity. The pressures in **Table 2** may appear to be lower than those found in various books or articles discussing wind loads on towers and antennas. Admittedly, this is an area of much confusion. Some people are familiar with standard EIA/TIA 222-E, while many more are familiar with the terminology of a prior version—EIA 222-C—issued by the Electronic Industries Association. In these references, factors for gusts and other "modifiers" are included in equations used to define wind pressure.[3,4] Here, **Equation 2** determines the dynamic wind pressure at the exact wind speed, V.[4] No additional factors are embedded to account for gusts or other effects.

Wind loading on an inclined member

An HF Yagi antenna usually consists of an assembly of tubes. Round tubes are used for the elements and another round tube, or assembly of round tubes, is used for the boom. Because the elements are mounted perpendicular to the boom, finding the resulting wind load of a complete antenna requires knowledge to determine the forces generated on each member when it's not broadside to the wind, but at some angle of attack. It is important to be able to determine the total wind load on the antenna for all angles relative to the wind to ascertain the worst case force that must be handled by the supporting tower system.

Figure 1 shows a tube inclined to a wind stream. When the angle is 90 degrees, we can use **Equation 3** to find the resulting force. For angles less than 90 degrees, the issue becomes more complex. To begin, we'll use the "cross flow principle."[5] To quote Dr. S.F. Hoerner from his book *Fluid-Dynamic Drag*, "At an angle of attack, ang, flow pattern and fluid dynamic pressure forces of such bodies only correspond to the velocity component (and the dynamic pressure) in the direction normal to their axis."[5] In **Figure 1**, the wind velocity component perpendicular to the tube causes a dynamic wind pressure that acts on the entire length of the tube. In other words, we have found the component of the wind velocity perpendicular to the tube and, knowing this, can use **Equation 2** to find the dynamic wind pressure perpendicular to the tube. We then use **Equation 3** to find the resulting force. With the tube inclined to the wind at an angle ang, **Equation 4** gives the velocity component perpendicular to the tube.

$$Vc = V \sin(ang) \qquad (4)$$

where:

Vc = wind velocity component perpendicular to the tube (MPH)
V = air velocity (MPH)
ang = angle of attack (deg)

Now that we can find the velocity component, Vc, we can use **Equation 2** to determine the dynamic wind pressure acting on the tube. Using **Equation 2** with Vc gives:

$$Pc = 0.00256\ Vc^2$$

where:

Pc = dynamic wind pressure on inclined tube at angle ang (psf)

Substituting **Equation 4** for Vc gives us **Equation 5**, which is in terms of the wind velocity and angle of attack.

$$Pc = 0.00256\ V^2 \sin^2(ang) \qquad (5)$$

In **Equation 5** the term $0.00256\ V^2$ is the value of P broadside to the wind, as defined in **Equation 2**. Based on this, we can rewrite **Equation 5** to obtain **Equation 6**.

$$Pc = P \sin^2(ang) \qquad (6)$$

This equation shows the resulting dynamic pressure on the tube, where P is the dynamic wind pressure broadside to the wind. Now that we can find the dynamic wind pressure acting on the tube, it's possible to combine **Equations**

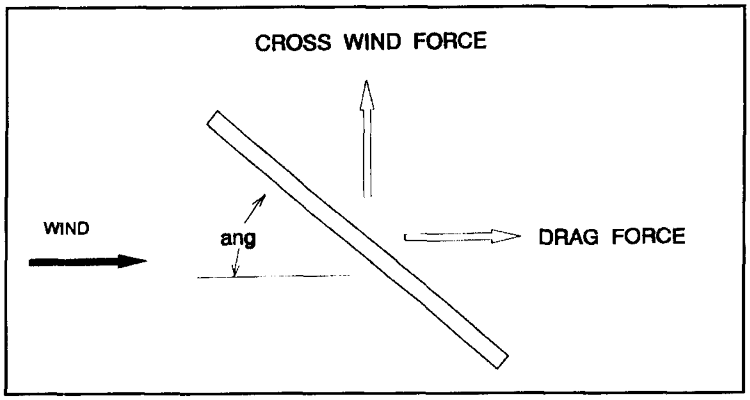


Figure 3. Drag and cross-wind forces on inclined tube.

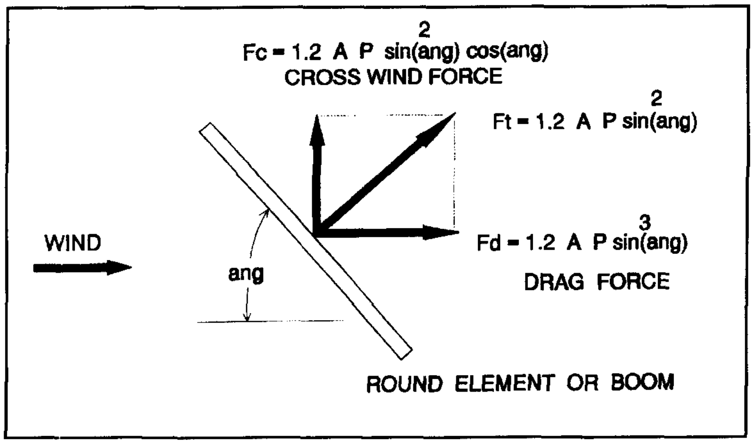


Figure 4. Drag and cross-wind forces.

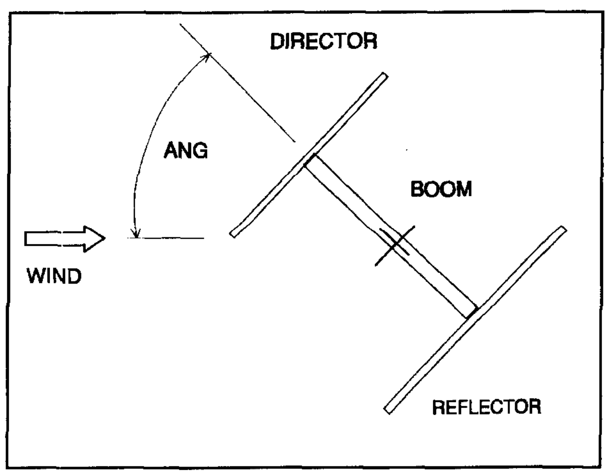


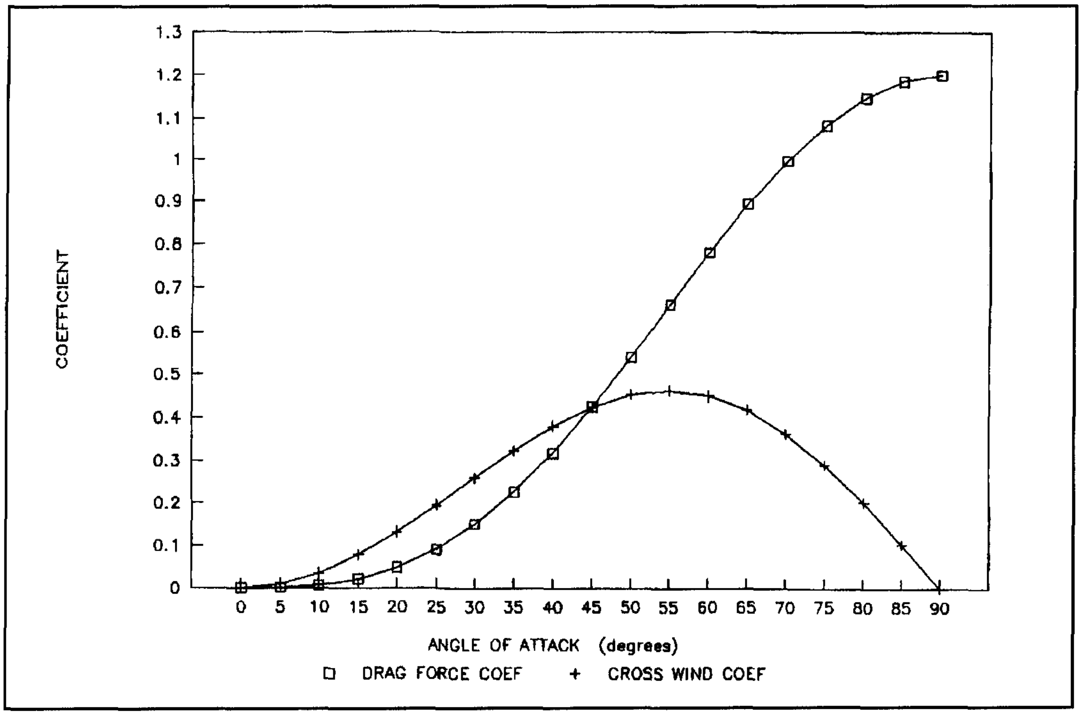
Figure 5. Simple example Yagi.

6 and **3** to form an equation which gives the force perpendicular to a object when it is inclined to a wind stream.

$$Fm = C\ A\ P \sin^2(ang) \qquad (7)$$

where:

Fm = force perpendicular to object (lbs)



Graph 1. Drag and cross-wind coefficients versus angle of attack.

Because we are mainly concerned with round tubes, C can be set equal to 1.2 in **Equation 7** to provide **Equation 8**. **Figure 2** illustrates Ft acting on a round tube inclined in a wind stream. Note that the "cross-flow principle" applies to all shapes, not just round objects. If the object was a flat plate, the value of the drag coefficient would be C = 2.[2]

$$Ft = 1.2\ A\ P\ \sin^2(ang) \qquad \textbf{(8)}$$

where:

Ft = force perpendicular to round tube (lbs)

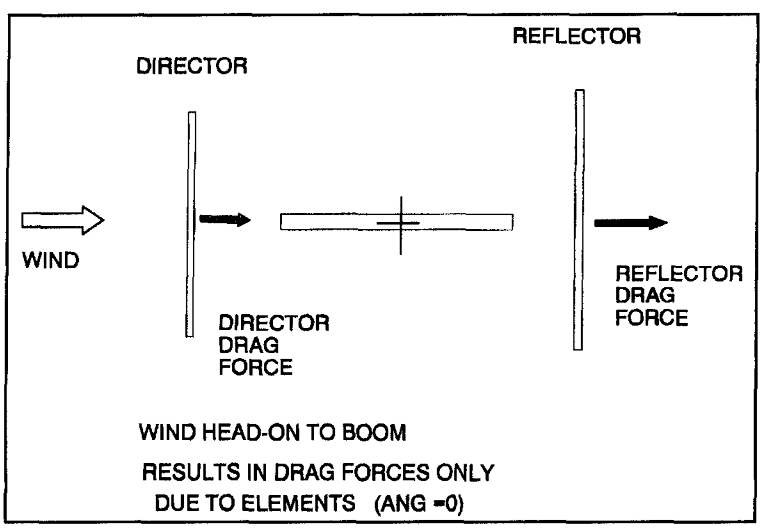


Figure 6A. Wind head-on to boom. (ang = 0).

P = 0.00256 V^2 (psf)
V = wind velocity (mph)
A = projected area of tube (square feet) (= length x diameter)
ang = angle of attack (deg)

When ang = 90 degrees, the wind velocity component perpendicular to the tube is the same as the stream velocity. With ang = 90 degrees, **Equation 8** yields:

Ft = 1.2 A P

which is the same as **Equation 3** with C = 1.2. This is as it should be, because **Equation 3** is for a tube broadside to the wind.

Please note that the projected area of the tube is still the broadside area found by the product of its length and diameter. In determining the force on an inclined tube, it is the component of the wind velocity that changes as a function of angle causing a variation in pressure loading. The change in force is **not** due to a difference in the tube area being exposed to the wind stream.

Drag and cross-wind forces

Equation 8 is used to find the force that results when a round tube is inclined at an angle in a wind stream. It is perpendicular to the tube, as shown in **Figure 2**. When there are multiple tubes in an assembly, it's common to simplify matters by finding the components of the tube forces which are in line and perpendicular to the wind. These forces are called the drag and cross-wind forces, respectively.[5,6,7] **Figure 3** gives an example that shows the cross-wind force, Fc, and the drag force, Fd, for the case in **Figure 2**. When there are multiple tubes, drag forces for all tubes are summed as are all cross-wind forces—making the accounting of the forces manageable. To do this, Ft is broken into the drag and cross-wind force components as shown in **Figure 4**. Fc and Fd are found using **Equations 9** and **10**, respectively.

$$Fc = Ft \cos(ang) \qquad \textbf{(9)}$$

where:

Fc = cross-wind force (lbs)

$$Fd = Ft \sin(ang) \qquad \textbf{(10)}$$

where:

Fd = drag force (lbs)

Substituting **Equation 8** for Ft in **Equations 9 and 10** yields **Equations 11 and 12** for Fc and Fd, respectively.

$$Fc = 1.2\ A\ P \sin^2(ang) \cos(ang) \qquad \textbf{(11)}$$

$$Fd = 1.2\ A\ P \sin^3(ang) \qquad \textbf{(12)}$$

If **Equations 11** and **12** were rewritten in the general form of **Equation 3**, a similar form would result, as shown in **Equations 13** and **14**. While **Equation 3** uses a fixed drag coefficient, C, **Equations 13** and **14** have an angle-dependent cross-wind coefficient, Cc, and an angle-dependent drag-force coefficient, Cd.

$$Fc = Cc\ A\ P \qquad \textbf{(13)}$$

$$Fd = Cd\ A\ P \qquad \textbf{(14)}$$

Where:

$$Cc = 1.2 \sin^2(ang) \cos(ang) \qquad \textbf{(15)}$$

$$Cd = 1.2 \sin^3(ang) \qquad \textbf{(16)}$$

The equations for Cc and Cd describe a variable coefficient as a function of the angle of attack. They are normally referred to as the cross-wind and drag coefficients for inclined tubes.[5,7,8] The behavior of these coefficients are shown in **Graph 1** which shows Cc and Cd as a function of angle. The drag force coefficient is maximum at ang = 90 degrees. This is expected as the tube is fully broadside to the wind. What's interesting is that the cross-wind coefficient peaks at 54.75 degrees, which

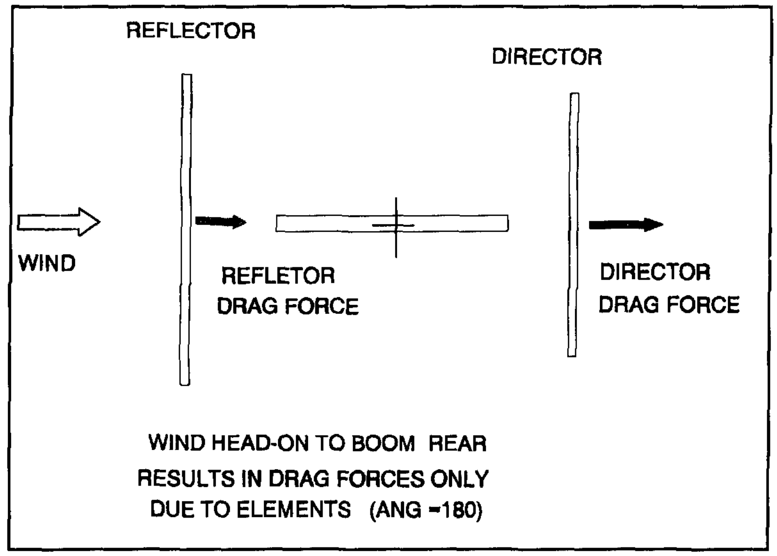


Figure 6B. Wind head-on to boom rear. (ang = 180).

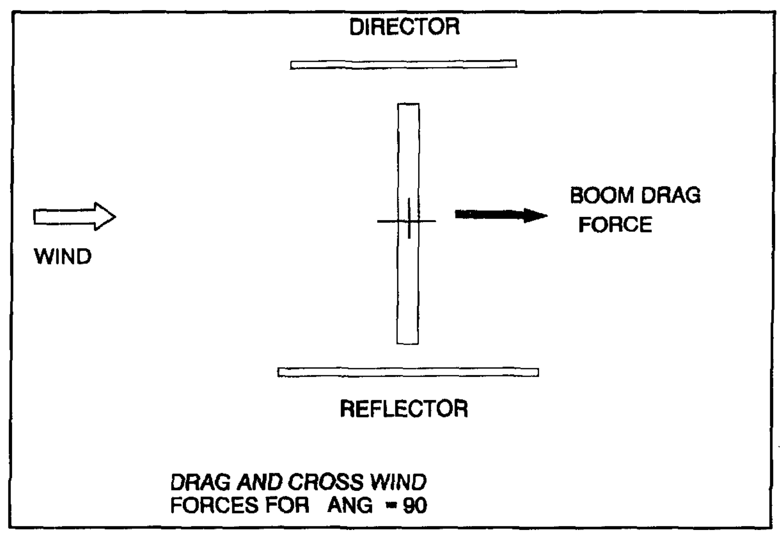


Figure 6C. Drag forces for ang = 90.

means the cross-wind force also peaks at 54.75 degrees. It's important to note that the cross-wind and drag-force coefficients are equal at 45 degrees. With these coefficients equal, the force produced in line with the wind is equal to the force produced perpendicular to the wind when a tube is 45 degrees relative to the wind.

There have been numerous experimental efforts that have verified Cc and Cd. Some were undertaken as early as seventy years ago.[5] Although not currently used in the amateur radio antenna field, many engineering books and references contain values for Cc and Cd. One of the more common references for engineers is *Mark's Standard Handbook for Mechanical Engineers*. On page 11–78 in the 9th edition, there's a chart for values of Cc and Cd at various angles between 0 and 90 degrees that agree with **Graph 1**.[7] *Mechanical*

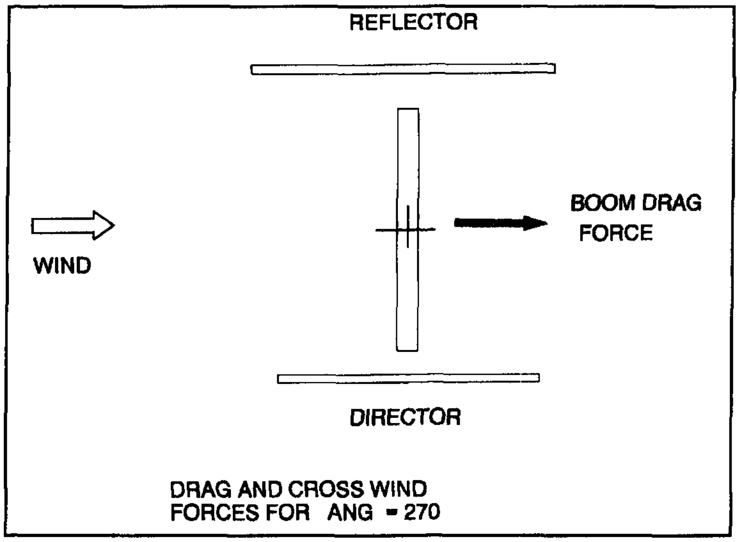


Figure 6D. Drag forces for ang = 270.

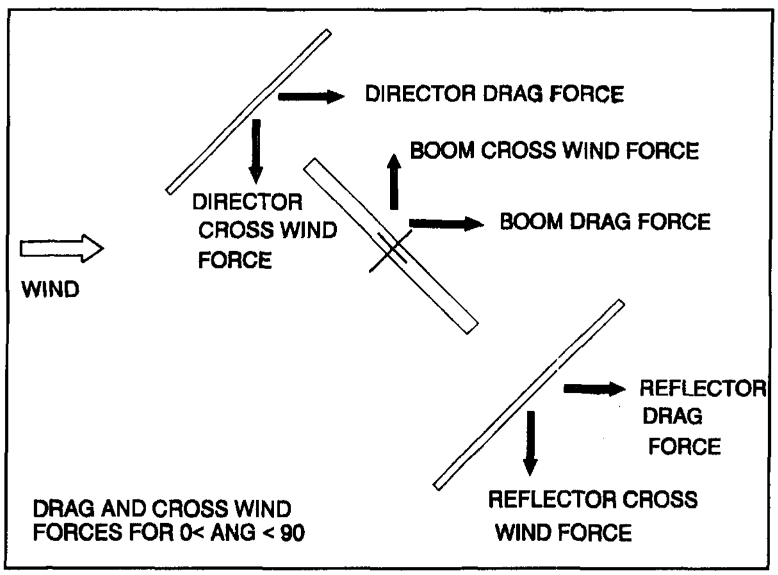


Figure 7A. Drag and cross-wind forces for 0<ang<90.

Engineering in Radar and Communications is a second book commonly used by mechanical engineers involved in antenna structural design. On page 165 of the 1969 edition, a diagram and chart are shown that also list the values of Cc and Cd for 0 to 90 degrees.[8] These, too, match **Graph 1**. The EIA/TIA 222E is a third reference that shows **Equations 15** and **16**. You'll find them on page 10.[9] And just recently, I found values for Cc and Cd in the building code for Richardson, Texas.[10]

Those interested in a discussion of the "cross-flow principle" may want to look at graphs of theoretical and experimental values of Cc and Cd on page 3–11 of *Fluid-Dynamic Drag*, 1965 edition.[5] As Hoerner's book illustrates, some of the earliest experimental verification for values of Cc and Cd was performed in 1919 by Alexandre Gustave Eiffel—a well-known engineer and aerodynamic researcher.[5] By the way, his tower is still standing!

Wind loads on Yagis with horizontal elements

Now that we know how to find cross-wind and drag forces for round tubes, we can find the total force loading of a Yagi. **Figure 5** depicts a simple Yagi with two horizontally mounted elements that we will use as an example. As the antenna is held at various angular positions relative to the wind, the loading gets somewhat complex. However, there are four positions that are easy to evaluate. We'll look at two positions where the elements are broad side to the wind and two where the boom is broadside to the wind, as shown in **Figures 6A** through **6D**. In the first two cases, only the elements experience the resulting forces; in the latter two cases, only the boom experiences the resulting force.

For angles between these four positions, the force loading becomes more complicated. **Figures 7A** through **7D** illustrate these cases. Two things become apparent. First, all drag forces are in the same direction. Second, the boom and element cross-wind forces are opposite each other because the two members are mounted at 90 degrees angles. It's easy to see why it is desirable to have the dynamic wind force broken into components which are in line and perpendicular to the wind. Doing so makes determining the net force a relatively easy matter using the force sign convention shown in **Figure 8**.

Because the elements are perpendicular to the boom, we use a slightly different set of equations to find the element cross-wind and drag forces. First, **Equations 11** and **12** are renamed to apply for the boom that results in **Equations 17** and **18**. **Equations 19** and **20** are for the elements, and account for the 90 degrees between the boom and the elements. Because elements are parallel to each other, their projected areas can be summed to Ae, while the boom projected area is Ab.

$$Fcb = 1.2\ Ab\ P\ \sin^2(ang)\cos(ang) \qquad \textbf{(17)}$$

$$Fdb = 1.2\ Ab\ P\ \sin^3(ang) \qquad \textbf{(18)}$$

where:

Fcb = cross-wind force for round boom
Fdb = drag force for round boom
Ab = boom projected area
ang = angle of attack of boom relative to wind (degrees)

$$Fce = 1.2\ Ae\ P \cos^2(ang) \sin(ang) \quad \textbf{(19)}$$

$$Fde = 1.2\ Ae\ P \cos^3(ang) \quad \textbf{(20)}$$

where:

Fce = cross-wind force for round elements
Fde = drag force for round elements
Ae = total element projected area

Let's start by concentrating on the case in **Figure 7A.** The cross-wind forces for the boom and elements are summed based on the sign convention in **Figure 8** to give the net cross-wind force.

$$Fcn = Fcb - Fce \quad \textbf{(21)}$$

where:

Fcn = net cross wind force (lbs)

The substitution of **Equations 17** and **19** into **Equation 21** produces a single equation for the net cross-wind force due to the boom and elements.

$$Fcn = 1.2\ P[Ab \sin^2(ang) \cos(ang) - Ae \cos^2(ang) \sin(ang)] \quad \textbf{(22)}$$

Similarly, we sum drag forces for the elements and boom to yield the net drag force.

$$Fdn = Fdb + Fde \quad \textbf{(23)}$$

where:

Fdn = net drag force (lbs)

Substituting **Equations 18** and **20** into **Equation 23** gives a single equation for the net drag force due to the boom and elements.

$$Fdn = 1.2\ P[Ab \sin^3(ang) + Ae \cos^3(ang)] \quad \textbf{(24)}$$

Some examples

Now that we've developed equations to describe the net cross-wind and net drag force, we'll consider several examples. First, let's look at a rather large Yagi consisting of horizontal elements with a boom area equal to that of the elements, Ab = Ae. To add some sense of magnitude, we'll set the areas at 10 square feet and calculate loads at an exact wind speed of 70 MPH. From **Table 2**, this puts P = 12.5 psf. The boom cross-wind force, element cross-wind force, and net cross-wind force for these values are shown in **Graph 2**. The boom, element, and net drag forces are shown in **Graph 3**. **Graph 2** indicates that the net cross-wind force is less the two individual cross-wind forces. This is expected, because the boom and element cross-wind forces are opposite each other, and their effects tend to cancel each other out. At the same time, **Graph 3** shows a dip in net drag force at 45 degrees.

Originally, forces were broken into components in line and perpendicular to the wind. This was done to allow the orderly summing of multiple forces. Now that we know the net cross-wind and drag forces, we must combine them to obtain the net force on the tower. This is done vectorially to provide Ftow, as shown in **Figure 9**. The angle wt is the angle of the net force on the tower relative to the wind. Ftow

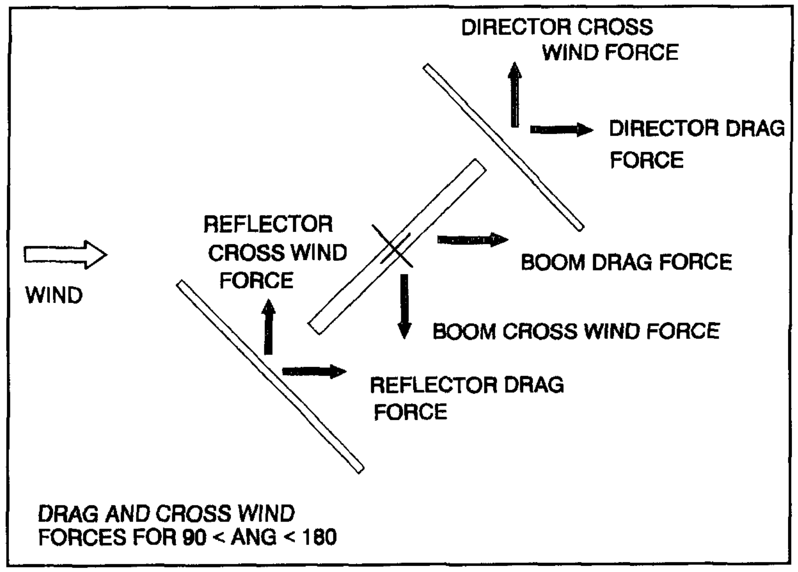


Figure 7B. Drag and cross-wind forces for 90<ang<180.

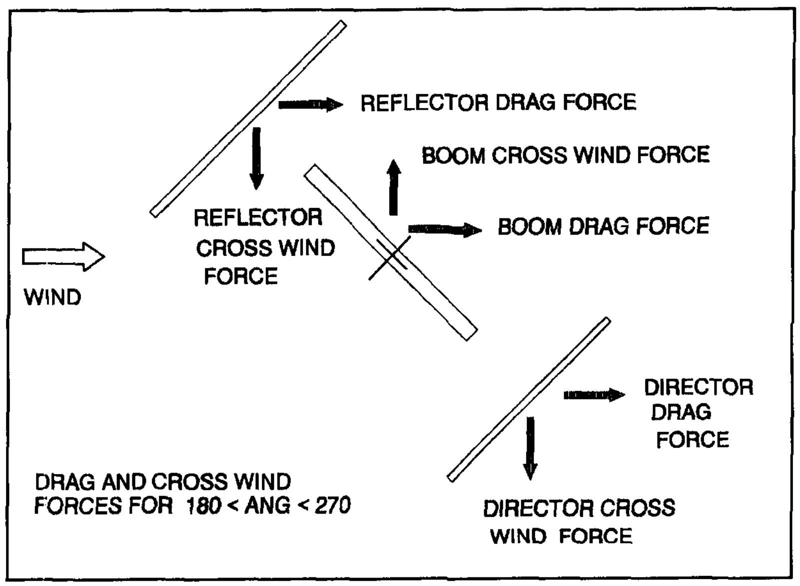


Figure 7C. Drag and cross-wind forces for 180<ang<270.

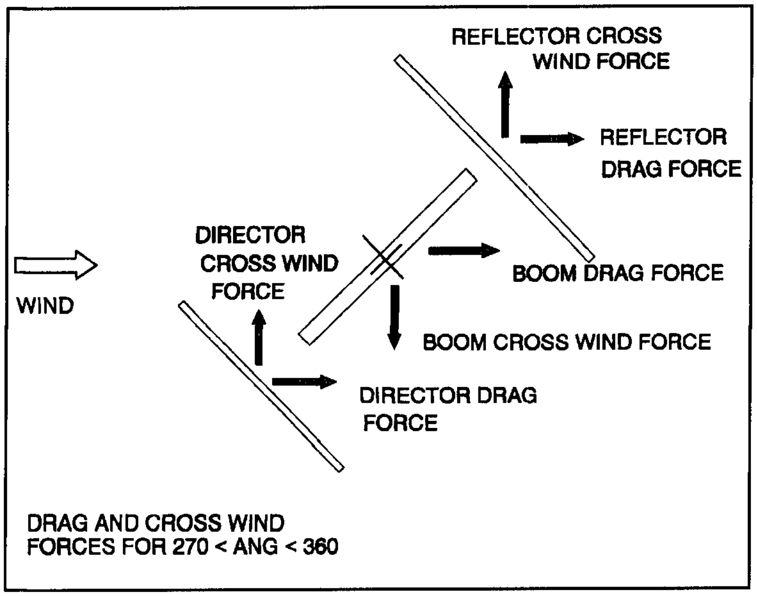


Figure 7D. Drag and cross-wind forces for 270<ang<360.

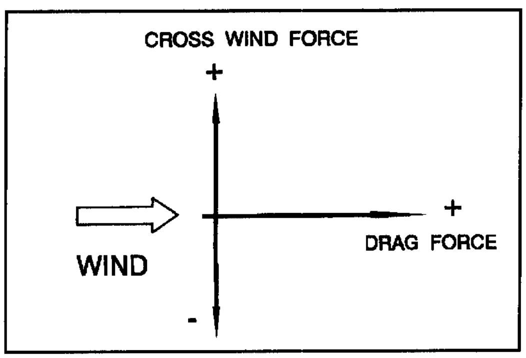


Figure 8. Force sign convention.

and wt are found using **Equations 25** and **26**, respectively. However, because the wind can come from any direction, knowing the wt is of little importance.

$$\text{Ftow} = [Fc^2n + Fdn^2]^{1/2} \qquad \textbf{(25)}$$

where:

Ftow = net force on tower (lbs)

$$\text{wt} = \tan^{-1}\left(\frac{\text{Fcn}}{\text{Fdn}}\right) \qquad \textbf{(26)}$$

where:

wt = angle of Ftow relative to wind direction (degrees)

Graph 4 gives the net force on the tower, Ftow, for the case shown in **Graphs 2** and **3**. The force levels at 0 and 90 degrees are expected to be the same, as the element and boom areas are equal. What may not have been expected is the force level at 45 degrees, where a minimum occurs. What does the method in current use say Ftow should be?

The "variable area" method (my name for it until a better one is suggested) says that Ftow is found by determining the total of the equivalent areas of the boom and elements broadside to the wind stream. The total broadside area is found using **Equation 27**. Then, **Equation 28** is used to find Ftow.[11,12]

$$\text{Aeff} = C\,[\text{Ae}\cos(\text{ang}) + \text{Ab}\sin(\text{ang})] \qquad \textbf{(27)}$$

$$\text{Ftow} = P\,\text{Aeff} \qquad \textbf{(28)}$$

In **Equation 27**, the terms Ae cos(ang) and Ab sin(ang) stand for the magnitudes of the element and boom areas that appear broadside to the wind stream. This is because it's assumed that the resulting wind forces are only in line with the wind, and a function of the broadside areas.[13] As you can see, this method doesn't account for the cross-wind forces or the true dynamic behavior of the loading. An additional misconception results from the "variable area" method. The method says there is a intermediate angle of attack between 0 and 90 degrees where Ftow peaks because Aeff has a corresponding maximum. The peak value of Aeff and the angle at which this occurs are found with **Equations 29 and 30.**[13]

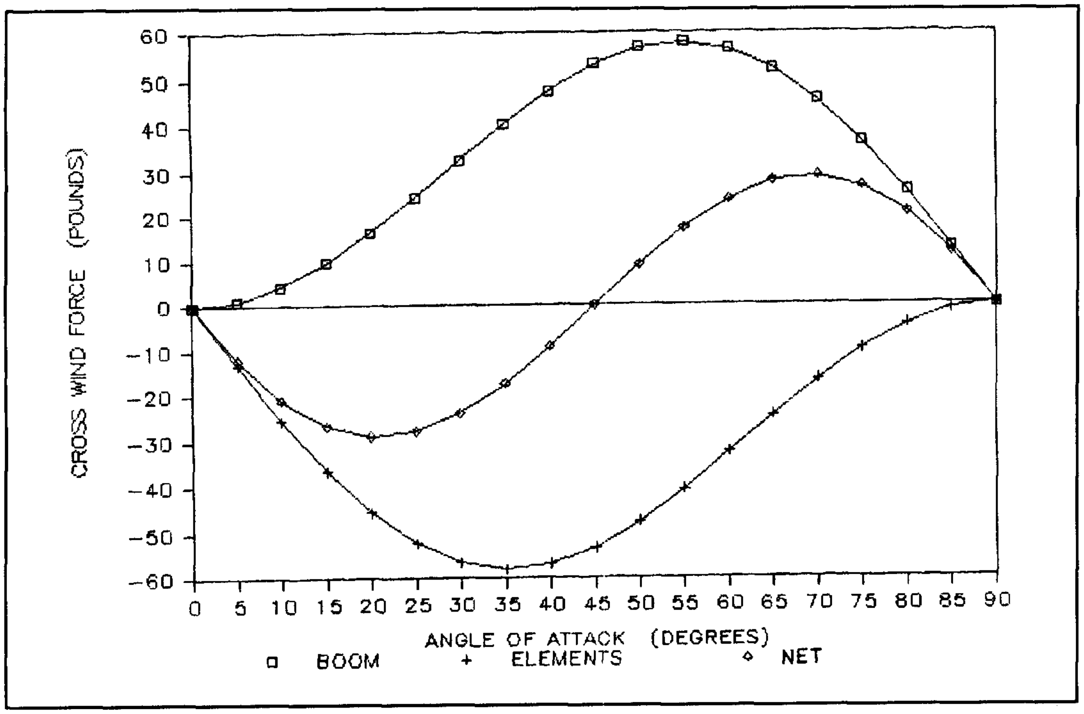
$$\text{Apeak} = C\,[Ae^2l + Ab^2]^{1/2} \qquad \textbf{(29)}$$

$$\text{angpk} = \tan^{-1}\left(\frac{\text{Ab}}{\text{Ae}}\right) \qquad \textbf{(30)}$$

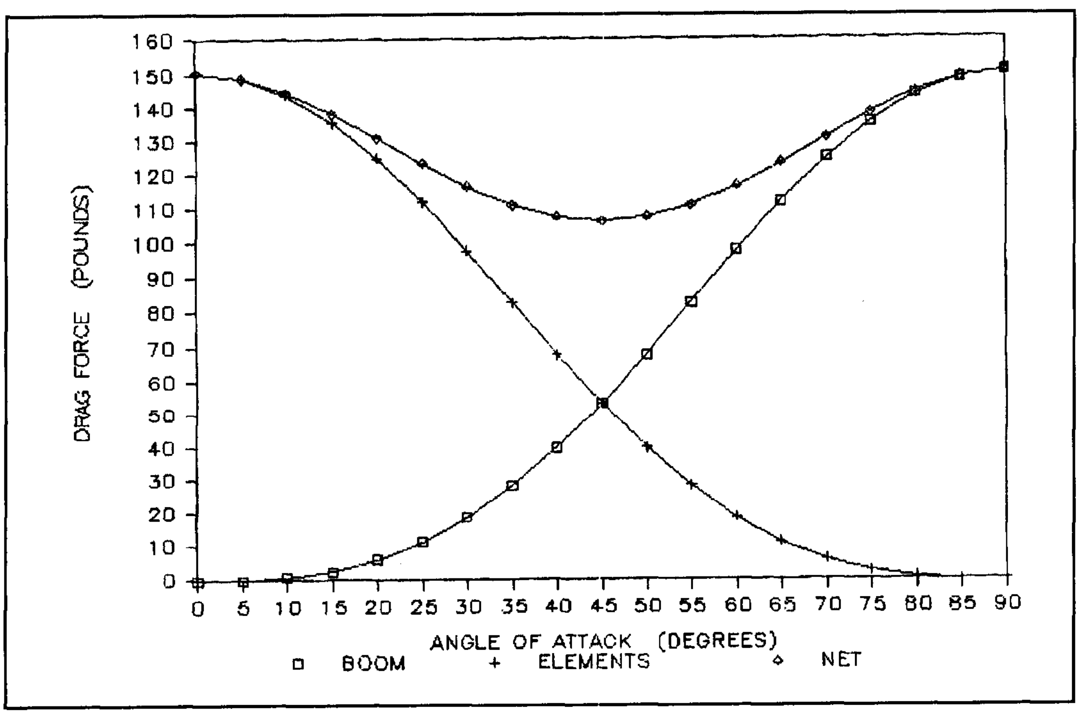
where:

Apeak = maximum effective area
angpk = angle of attack at which maximum area occurs(degrees)

Using the same boom and element areas from the present example, **Graph 5** shows a comparison of Ftow derived by the "cross-flow principle" and the "variable area" method. Two things are evident. First, the magnitude prediction for Ftow is 41.4 percent too high when determined by the "variable area" method. Second, the angle of attack for maximum Ftow is off by 45 degrees. At first, it might seem illogical that the maximum net wind load isn't at some angle between 0 and 90 degrees. This is easily explained. As **Graph 3** illustrates, the element drag force falls off more rapidly than the boom drag force increases, as the angle of attack increases from 0 degrees. At the same time, there isn't much contribution to Ftow from the cross-wind forces, as they tend to



Graph 2. Yagi cross-wind forces. Ab = Ae = 10 square feet/70 mph.



Graph 3. Yagi drag forces. Ab = Ae = 10 square feet/70 mph.

negate each other. Also, because the net cross-wind force is relatively small when compared to the net drag force, its contribution is minimized when combined vectorially with the net drag force.

Let's look at two more examples using a wind velocity of 70 mph. The first has a boom of 5 square feet, Ab = 5, and a total element area of 10 square feet, Ae = 10. **Graph 6** shows the element, boom, and net cross-wind forces. Again, we can see that the net cross wind is less than the largest individual contributor. **Graph 7** gives the element, boom, and net drag forces. This behavior isn't unexpected at 0 and 90

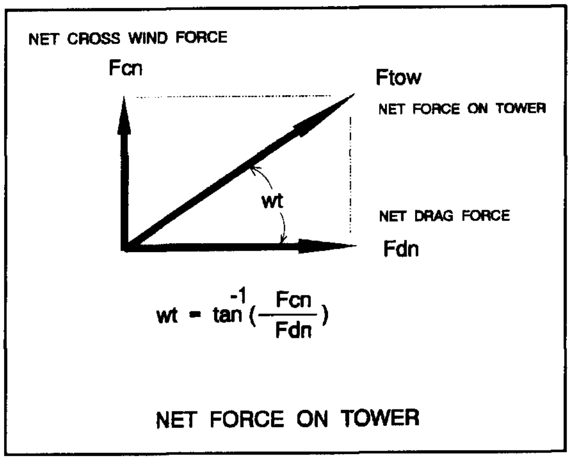


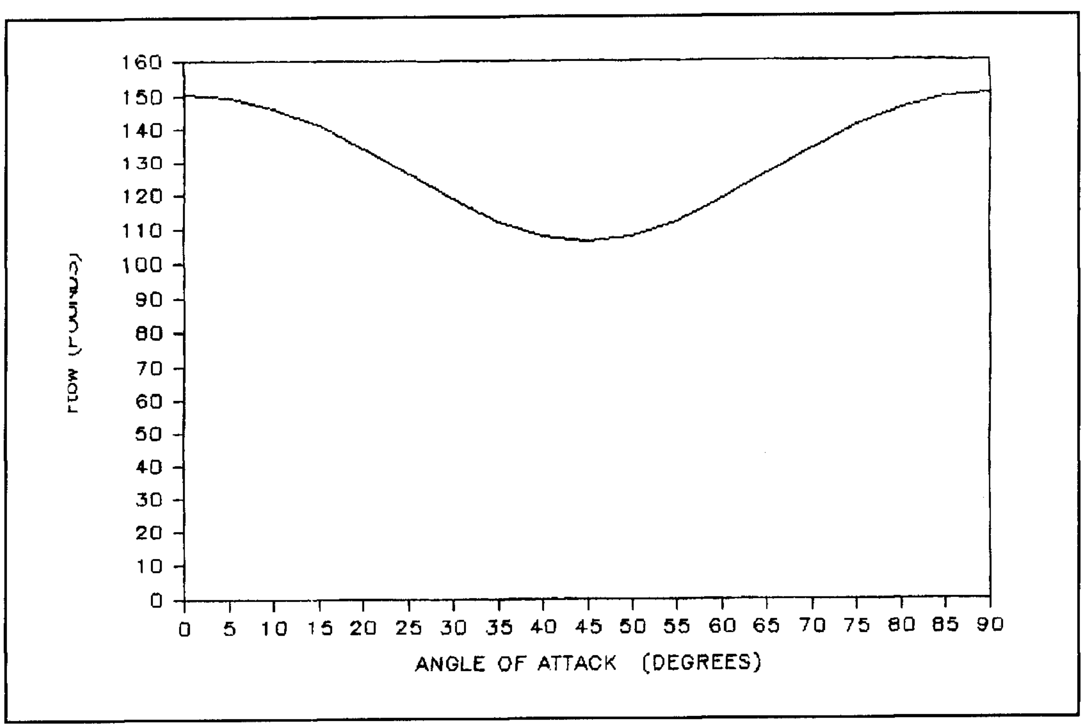
Figure 9. Net force on tower.

degrees due to the different boom and element areas. **Graph 8** shows the net force on the tower, Ftow. It also shows that the highest loading is encountered when the elements are broadside to the wind, and not at some intermediate angle of attack. In the second example, the element and boom areas are reversed, Ab = 10 square feet and Ae = 5 square feet. **Graph 9** shows the cross-wind forces, **Graph 10** the drag forces, and **Graph 11** the net force on the tower. **Graphs 8** and **11** once again indicate that there's no intermediate angle of attack where Ftow is greater than the force produced when the larger of the boom or total element area is broadside to the wind.

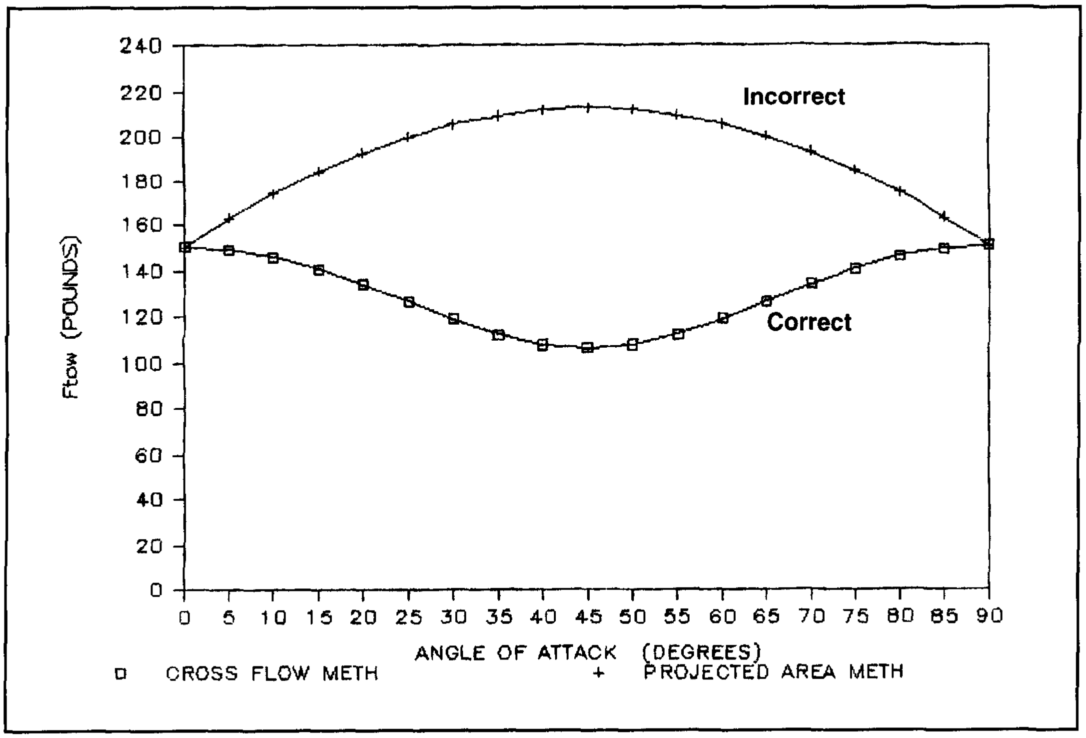
When the boom has a greater area than the elements, the boom area determines the highest load imposed on the tower. The opposite is also true. When the elements have more total area than the boom, the element area determines the highest tower load. For the unique situation where the boom area and total element areas are the same, there are two angles of attack—0 and 90 degrees—where the same peak value of Ftow is developed. **Graphs 4, 8,** and **11** show Ftow for 0 to 90 degrees. **Graphs 12, 13,** and **14** show Ftow for 0 to 360 degrees of rotation for the same cases, respectively. These last graphs show that Ftow behaves as expected for a full 360 degrees of rotation.

Summary review

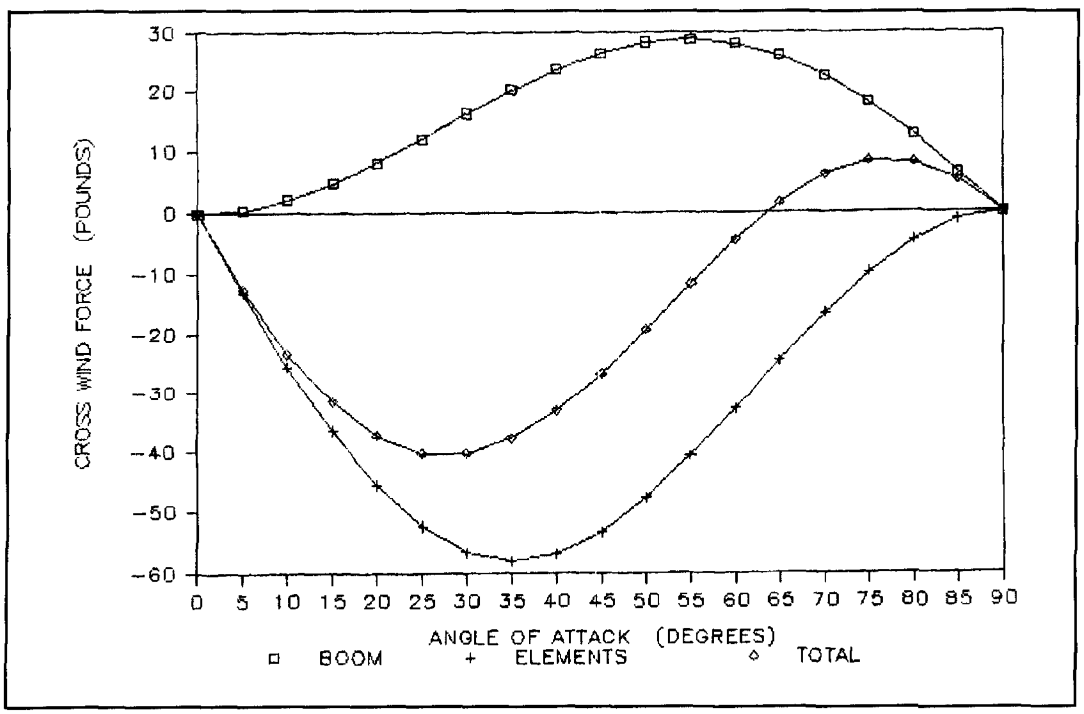
The force developed on a round tube inclined to a wind stream is perpendicular to the tube as shown in **Figure 2** and is found using **Equation 8**. In **Equation 8**, A is the projected area of the tube, which is its length times its diameter. To make it a simple matter to find the net force on a tower, forces produced by horizontally mounted elements and boom are broken into components perpendicular to the wind and in line with the wind. The forces perpendicular to the wind are the cross-wind forces found using **Equations 17** and **19**. The drag forces found by **Equations 18** and **20** are forces in line with the wind. Building on these equations, three others result that let us find the force on the tower, Ftow, directly. These are **Equations 22, 24,** and **25**. **Equation 22** gives



Graph 4. Net force on tower, Ftow. Ab = Ae = 10 square feet/70 mph.



Graph 5. Net force on tower, Ftow. Ab = Ae = 10 square feet/70 mph.

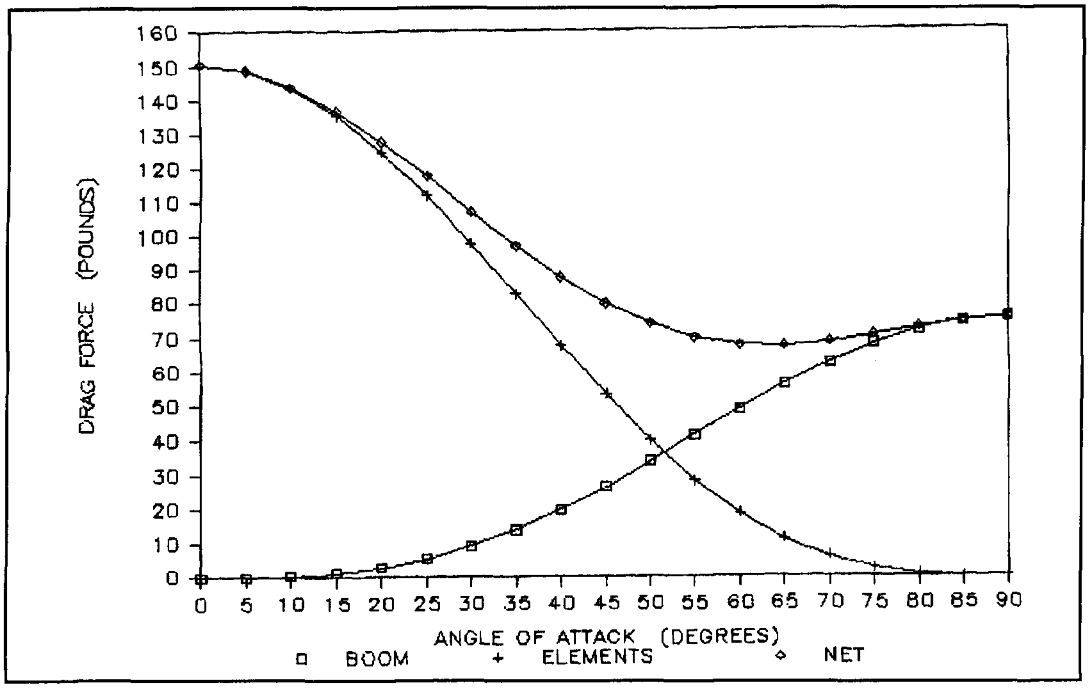


Graph 6. Yagi cross-wind forces. Ab = 5 square feet/Ae = 10 square feet/70 mph.

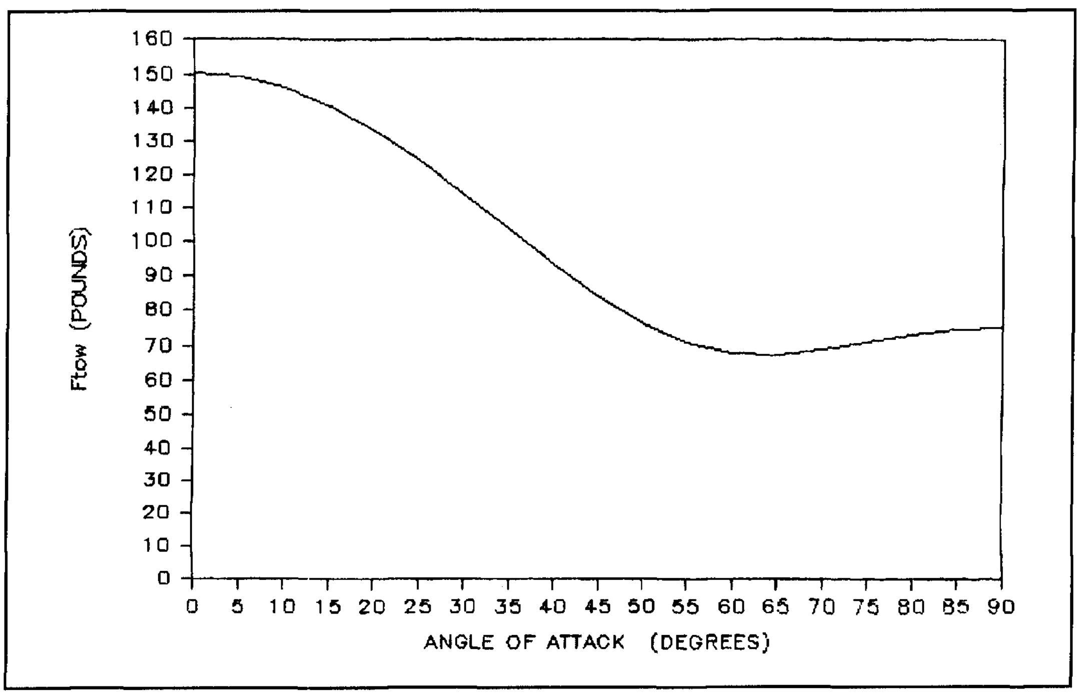
the resultant cross-wind force, **Equation 24** the resultant drag force, and **Equation 25** the vector sum of the cross-wind and drag forces. Ftow from **Equation 25** provides the net loading on the tower.

For more information on using the "cross-flow principle", review **References 5** and **6.** These will show the mathematical formulation and verifying experimental results. Although the use of the "cross-flow principle" to evaluate wind loads on amateur Yagis is new, the method is not. Some of the earliest experiments verifying it are over seventy years old.[5]

Reference 13, which discusses the incorrect



Graph 7. Yagi drag forces. Ab = 5 square feet/Ae = 10 square feet/70 mph.

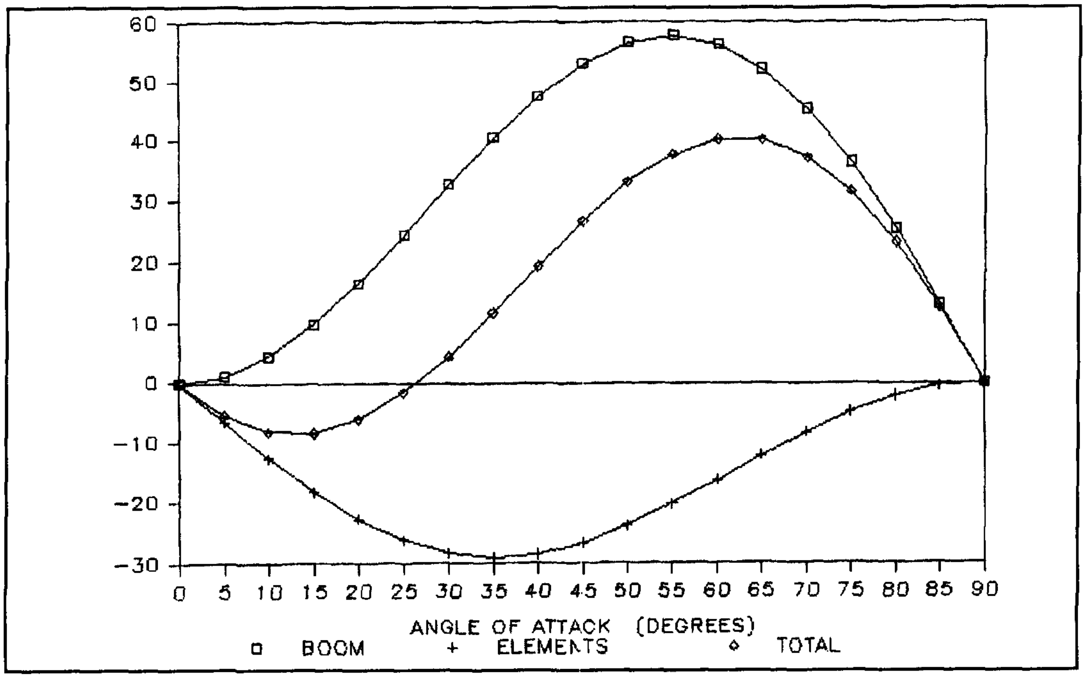


Graph 8. Net force on tower, Ftow. Ab = 5 square feet/Ae = 10 square feet/70 mph.

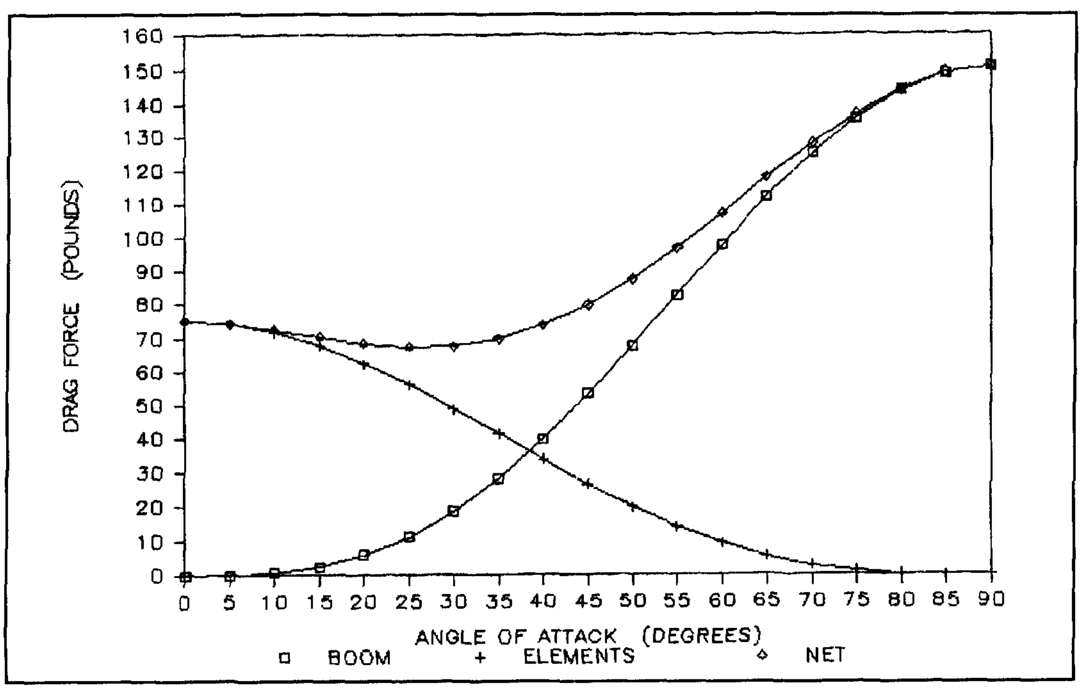
method, states: "The wind force acts only in the direction of the wind..."[13] The following simple test demonstrates that force components are also developed perpendicular to the wind stream direction. Two people take a 24 to 36-inch length of round tubing about 1 inch or more in diameter for a car ride. One person drives while another sits in the passenger seat. The passenger holds the tube in his hand, and puts his arm out the window positioning the tube straight up and down. The tube is now perpendicular to the wind stream. With the tube broadside to the wind stream, it's easy to observe a force (drag force) in line with the wind. The passenger now rotates the tube 45 degrees, top end forward. There is not only a much smaller drag force, but also be an upward push due to the cross-wind force. At a different angle of attack, when the tube is turned 45 degrees to the wind, lower end forward, the cross-wind force pushes downward. Using this simple test, it's possible to prove that the basic assumption of the "variable area" method is incorrect and, at the same time, verify the basic nature of the "cross-flow principle."

The Challenge

In the course of preparing this article, I wrote to five major amateur radio antenna manufacturers and asked how they determined wind loading effects for their Yagis. All but one, use the "variable area" method to derive a "surface area" (sic) for their antennas using **Equation 29**. The remaining manufacturer uses the sum of the element and boom areas. In both instances, the intent is for the stated surface area to be multiplied by the dynamic wind pressure to find the resulting wind load. Using these methods, all have overstated the parameters



Graph 9. Yagi cross-wind forces. Ab = 10 square feet/Ae = 5 square feet/70 mph.



Graph 10. Yagi drag forces. Ab = 10 square feet/Ae = 5 square feet/70 mph.

used to find the wind loads produced by their antennas. One manufacturer does so by taking an extremely conservative approach. The others, using the "variable area" method, also overstate the parameters used to determine the resulting wind loads—demonstrated by the example used to generate **Graph 5**.

A quick look at the surface area specifications for two very similar antennas from two different manufacturers shows that one, or both companies, is not doing what it says it does when determining the "surface area" of its antenna. Also, there is at least one manufacturer who doesn't include the area of the boom-to-mast plate in the wind load. The manufacturer claims this plate is part of the mast. I'm not sure about the masts sold outside of Texas, but here, when you buy a mast, you don't automatically get a boom-to-mast plate which, quite coincidentally, fits your beam. After a little investigation, it becomes apparent there is need for a standard method to find the wind loading effect of Yagis, and that it should be based on the "cross-flow principle." This standard should be used by all manufacturers, because it would allow the consumer to make an accurate comparison of antenna specifications. Also, having a technically correct standard would allow for valid structural evaluations of Yagi installations. The challenge? To establish a technically correct standard.

Establishing the standard

Most Yagi antennas are made from round tubes and flat plates, although some designs have other shapes—like molded element insulators or formed mounting brackets. The challenge is to establish a standard that recognizes these different shapes. A few simplifications are required to make the standard straightforward. Otherwise, it will get bogged-down in the intricacies of defining the wind loading for all possible shapes used for element mounting and boom-to-mast plates.

The first simplification is that all parts of a Yagi which aren't round must be treated as flat areas. Because Yagis mostly consist of round tubes and flat plates, any error induced by treating a molded part as a flat plate will be extremely small. The "cross-flow principle" applies to all shapes—not just round tubes. Therefore, the equations for the cross wind and drag forces for round tubes apply for flat plates with only a change in the drag coefficient. Although equations derived here have concentrated on round tubes with a drag coefficient of 1.2, the same equations apply for flat plates with a drag coefficient of 2.0. All that's needed is an inventory of the round and flat areas. Round areas have a 1.2 drag coefficient applied and flat areas have a 2.0 coefficient. This means that flat plates and round tubes can be combined to provide useful parameters that describe wind loading effects. The required parameters would describe instances when the elements are broadside to the wind and when the boom is broadside to the wind.

This can be handled by defining two load factors, E and B. E would account for wind loading effects with the elements broadside to the wind, and B when the boom is broadside to the wind. Factors E and B would have areas and respective drag coefficients embedded so a simple equation could be used to find the worst-case wind load.

Because there is no intermediate angle of attack between 0 and 90 degrees where Ftow peaks, the larger of E and B would be used to find the worst-case wind load. To do so, one would use **Equation 31** with the larger of E and B.

$$\text{Fmax} = (\text{E or B})\ \text{P} \qquad \textbf{(31)}$$

where:

Fmax = maximum value of Ftow
E = element load factor (square feet)
B = boom load factor (square feet)
(use the larger of E and B)

Equation 32 shows how to determine the boom load factor with the boom broadside to the wind. This equation takes into account the projected areas of the round and flat parts making up the antenna. It also considers the boom-to-element connection viewed "boom broadside," as shown in **Figure 10**.

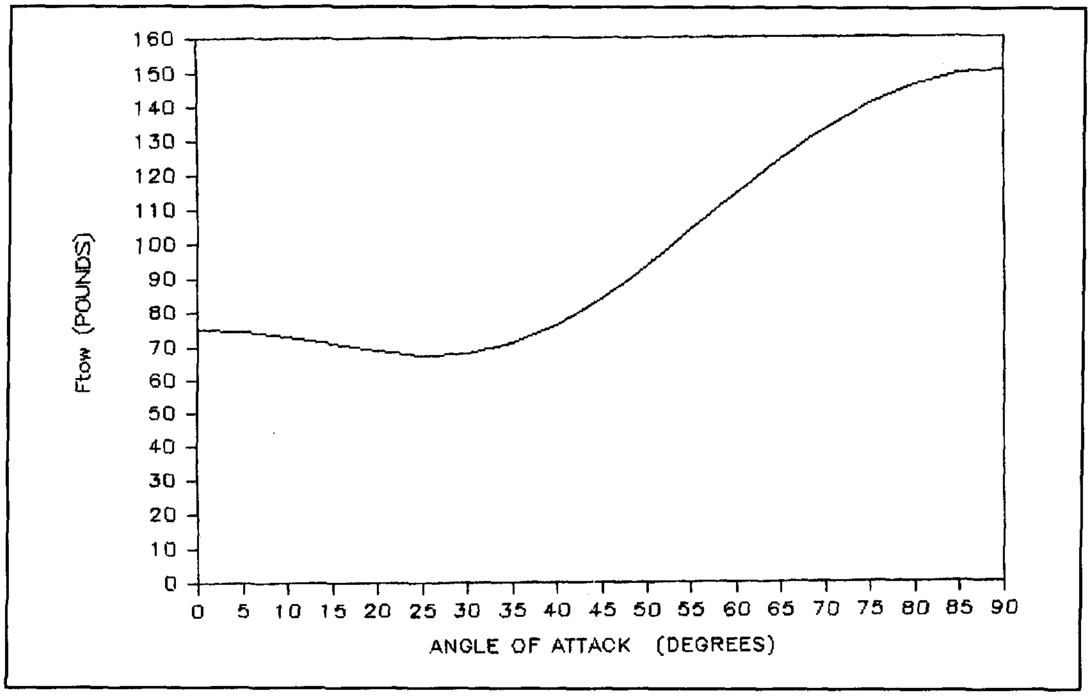
$$\text{B} = 1.2\ \text{Ab} + 2.0\ \text{Abp} + 2.0\ \text{Aet} \qquad \textbf{(32)}$$

where:

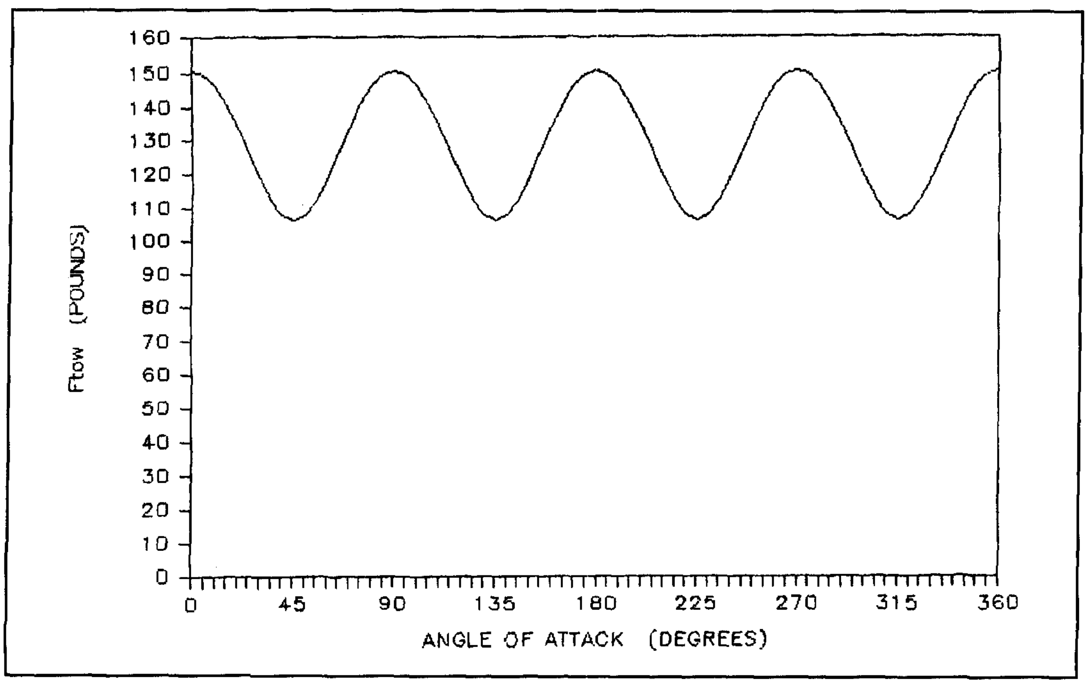
B = boom load factor (square feet)
Ab = exposed boom area (square feet)
Abp = boom flat plate area (square feet)
Aet = total element end area (square feet)

In the case of the boom-to-mast plate shown in **Figure 10**, the broadside area of the plate, Abp, is used while the area of the boom behind it is not, because the plate shields the boom. Although the actual drag coefficient in this area is a little less than 2.0, there's very little error introduced by following this methodology. More importantly, this methodology is easy to follow and understand. The area highlighted by the circle and enlarged in **Figure 10** shows the recommended way to handle the element mounting plate and the area presented to the wind by the end of the element. The area of the box is taken as a flat plate area. This is done for each element and the areas summed to obtain Aet. The exposed boom area, Ab, is then the area of the boom not shielded by the boom-to-mast plate and not enclosed in the "boxes."

Determination of the element load factor follows a similar pattern as shown in **Equation 33** and **Figure 11**. The term Ape denotes any flat plate that may be attached to the boom or elements, is broadside to the wind, and is not used to mount the elements. Only in a very rare instance would there be such a plate. The boom end cross-section area is used to account for the boom end. For example, if the boom has a 2 inch diameter at its end, Abe would be the area of a 2-inch diameter circle. Admittedly, for HF Yagis the boom end area will be very small



Graph 11. Net force on tower, Ftow. Ab = 10 square feet/Ae = 5 square feet/70 mph.



Graph 12. Net force on tower, Ftow. Ab = Ae = 10 square feet/70 mph.

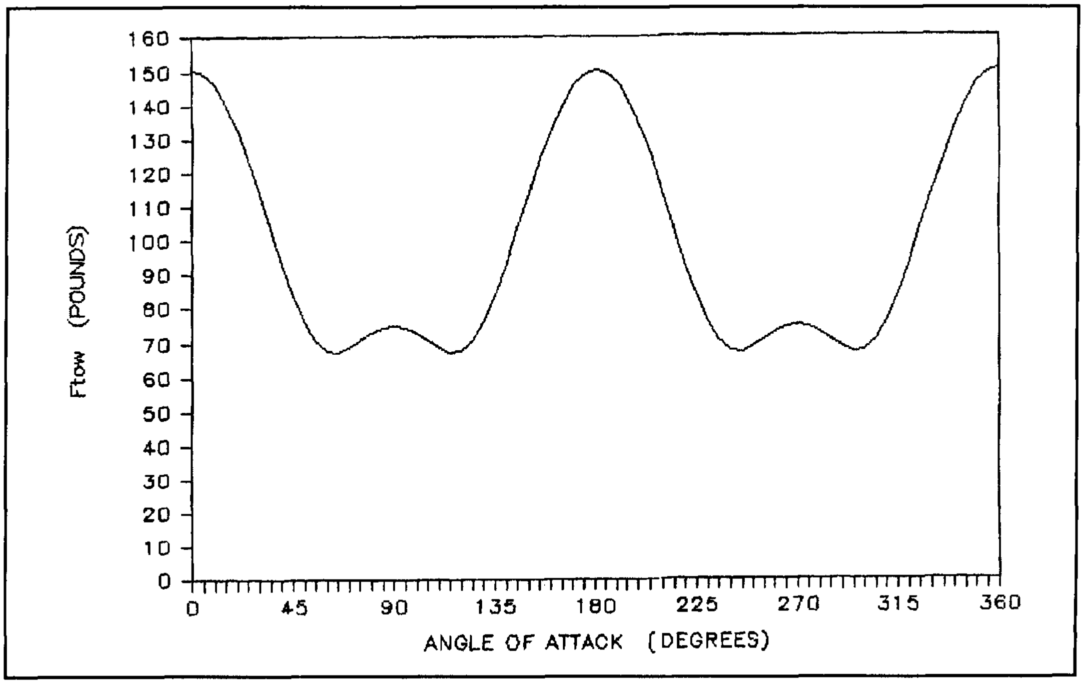
compared to the area of the elements, but it may be a significant contributor to E for UHF and higher frequency Yagis.

$$E = 1.2\ Ael + 2.0\ Ape + 2.0\ Abe + 2.0\ Aem \quad \textbf{(33)}$$

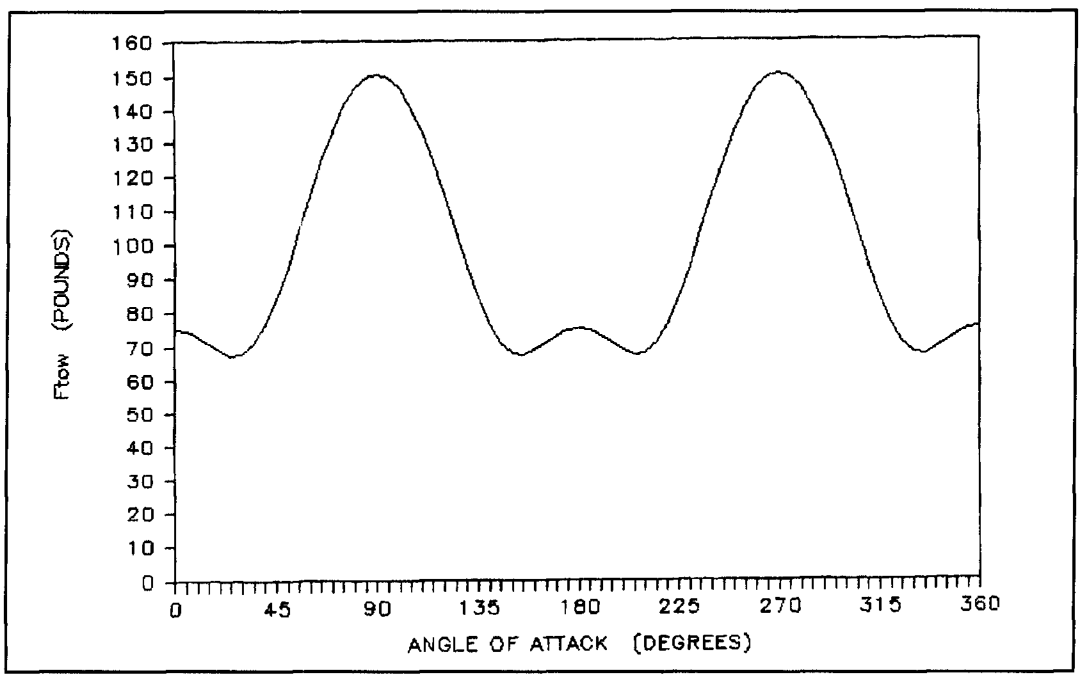
where:

E = element load factor (square feet)
Ael = total element area (square feet)
Ape = flat plate area (square feet)
Abe = boom end area (square feet)
Aem = total element mounting area (square feet)

Most Yagis use relatively thin plates to mount elements to the boom. However, there are cases where molded insulators, which generally have considerable broadside area, are used to isolate the elements from the boom. To



Graph 13. Net force placed on tower, Ftow. Ab = 5 square feet/Ae = 10 square feet/70 mph.



Graph 14. Net force on tower, Ftow. Ab = 10 square feet/Ae = 5 square feet/70 mph.

account for the contribution of mounting plates or insulators, I recommend the method shown in **Figure 11**. The enlarged area shows the mounting plates and the mating element length enclosed by a "box." Find the area of the "box" for each element and then sum the areas to obtain Aem in **Equation 33**. This area is also treated as a flat plate area. Obtain Ael by finding the broadside area of each element, but not using that within each "box," and summing them to give the total element area. Again, there are some minor errors that occur when using the "boxes," but the contributions of the enclosed items are accounted for using a simple, understandable, methodology.

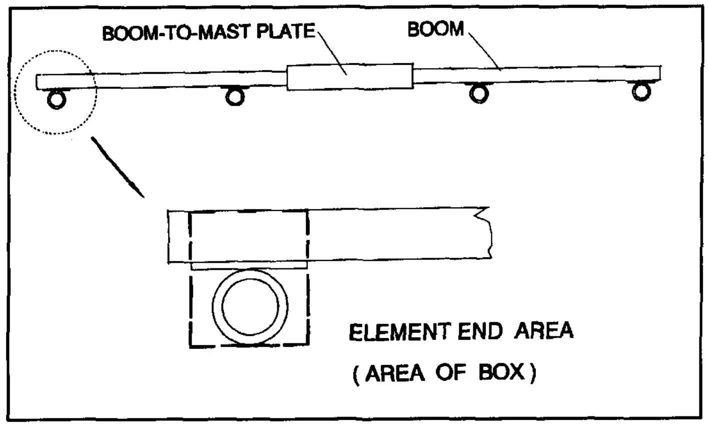


Figure 10. Boom broadside.

Finding the maximum force

Follow the methodology for the boom-broadside case using **Equation 32** and the element-broadside case using **Equation 33**. After finding the load factors, select the larger of them to find the maximum force. Once you've found B and E (either by "cranking" the numbers or hopefully, in the future, obtaining them from a manufacturer's specification sheet), use the larger in **Equation 31**.

The value of P depends on the wind conditions for your installation and the antenna height. There are several ways to find out the value of wind velocity and set of modifying factors for gusts and tower height you should use. EIA Standard EIA/TIA-222-E is one of the best sources of information.[9] In this standard, wind conditions are now specified by county rather than in map form. Also given are equations to find allowances for antenna height and gusts. You can also check to see what is required by the building code for your area. Building codes generally state conditions deemed to be worst case for your area. In areas of very high wind, you might be well advised to consult local government agencies, like the weather bureau, to see what information they can provide.

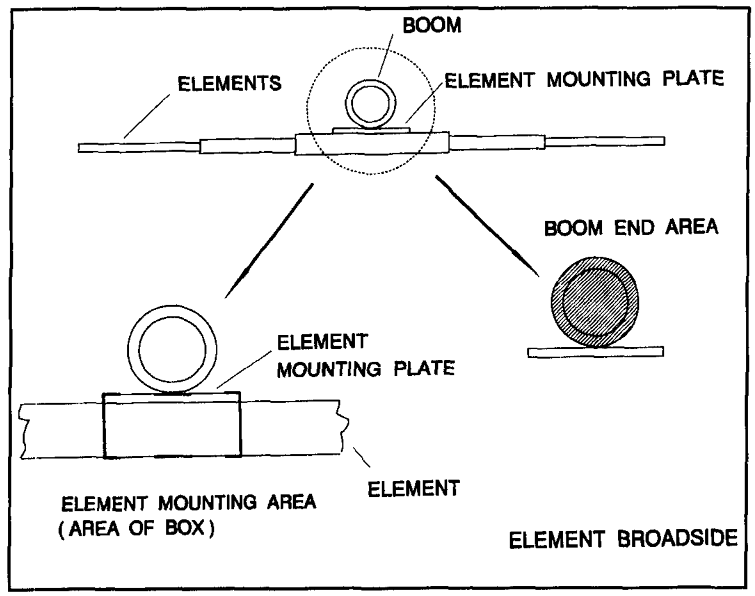


Figure 11. Element broadside.

When comparing different antenna models, you would compare the E and B load factors. Also, by knowing both factors, you would know which way to point your beam to minimize the wind loading during storms.

Yagi wind loading standard

The standard recommended here is very simple. Use **Equations 32** and **33** to find boom and element load factors. Manufacturers should list these two parameters in their specification sheet. Manufactures should **not** state wind forces at a specific wind speed—as this doesn't account for local conditions, gusts, antenna height, and other conditions that control the dynamic wind pressure. Once you know the two load factors, its simple to use **Equation 31** to find the maximum tower load based on the dynamic wind pressure unique to your location.

Summary

For at least the past 25 years, an incorrect method has been used to determine Yagi wind loads. The "variable area" method currently employed by manufacturers, discussed by numerous authors, and used in amateur mechanical design software has no basis in science, experimental evidence, or fact. Using the "cross-flow principle," forces due to wind can be predicted correctly. The "cross-flow principle" has been known and used for many years by mechanical, civil, and aeronautical engineers. There is an abundance of experimental verification regarding this principle—some of which dates back to 1919.[5]

Use of the "cross-flow principle" shows that larger wind loads result with the boom broadside to the wind and the elements broadside to the wind. The larger of the two presents the worst case. There is no intermediate position that produces a higher load; quite the contrary is true. There is a minimum between the two broadside positions. The only information needed to determine the wind loads at both broadside orientations are the E and B load factors. I recommend that manufacturers and individuals use these two factors when stating the wind loading aspects of their designs.

I hope that antenna manufacturers will adopt the methodology discussed here, and that the E and B load factors will be used in product specification sheets to correctly describe antenna wind loads for Yagis with horizontally mounted elements. I invite those interested in this topic to review the cited references. I'd like to state once again that the "cross flow principle" isn't new. It just hasn't been used, while the current method has gone unquestioned for many years. Needless to say, I look forward to vigorous discussions on this topic. ■

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PRODUCT INFORMATION

Radio Spectrum Explorer™ for Windows

Advanced Computer Controls introduces Radio Spectrum Explorer software for Windows. Explorer is a new user interface for your VHF and UHF communications receiver.

Explorer offers different perspectives on operating the radio through several windows—Frequency, Description, SuperMemory™, Spectrum Chart, and Map windows. The *Frequency window* most closely resembles a radio's conventional front panel, although it is enhanced to make it easier to "tune around." Other windows provide new perspectives on spectrum exploration.

The *Description window* displays information about the channel selected. It shows nationwide FCC allocation information, along with easily edited local information panels to show the radio user description, detail, locations, callsign, and service.

With Explorer, memories are organized in a hierarchy called *SuperMemories.* Folders contain frequencies, groups (like trunking groups), tuning ranges, and more folders. The multi-level folder hierarchy uses descriptive names and icons resembling file management on moder computers.

The *Map window* lets you tune using geographical maps of a specific area. Maps are obtainable from a program like *Street Atlas USA* or *AutoMap,* or by scanning printed maps into the computer.

The *Spectrum Chart window* is analogous to a printed spectrum wall chart, but appears onscreen, instead.

Radio Spectrum Explorer is fully Windows compliant, and its operation resembles other popular Windows programs. It has its own Help file which serves as a thorough on-line hypertext manual. A status line in each window continually feeds back information about how to use the program.

System requirements include a personal computer using a 386SX-25 or higher processor running Windows 3.1, and a receiver with a computer port and level converter. Several radios *without* computer ports will also be supported in the future with hardware options.

ACC produces microcomputer based control systems and software for amateur, commercial, and government radio users. For more information, contact Advanced Computer Controls, Inc., 2356 Walsh Avenue, Santa Clara, California 95051, or call 1-408-727-3330.