PROPELLER FATIGUE

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ALL AIRPLANE PROPELLERS are rather shaky devices. That is, they all vibrate while in motion. Vibration increases the stresses in a propeller and, if the level is high enough, it can cause serious trouble.

Wood has the desirable characteristic that it tends to dampen vibration. Its high internal friction absorbs energy making it a poor quality spring. For this reason, wooden propellers generally do not suffer from fatigue due to vibration.

On the other hand, propellers made of aluminum alloy have low internal friction damping and every one must be carefully designed to prevent severe vibration at rotational speeds where the engine will operate a significant percentage of the time. Metal has a very high strength compared to wood, but it will not tolerate being repeatedly loaded to high stress levels. It effectively gets "tired" and "wears out" after a certain predictable number of cyclic load applications and will eventually break.

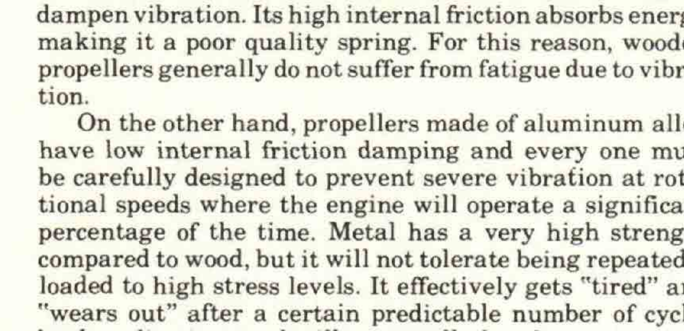

Figure 1. SN Curve for Aluminum in Notched Condition

The number of load cycles which a given metal member will withstand is a function of the stress level as shown in Figure 1. As the stress level is decreased, the metal will withstand more and more cycles. At some stress level the member can be cyclically loaded an almost infinite number of times without harm. Experience has shown that for aluminum alloy used in propellers, when allowance is made for service nicks and scratches, this level is 4700 pounds per square inch with a safety factor of about two. Some propellers have been certificated with operating stresses as high as 6000 psi. Higher stresses can be experienced safely for a limited number of cycles but, when the fatigue limit is exceeded, metal life is being used up. Virtually all metal propellers exceed the fatigue limit when they are caused to vibrate at certain resonant frequencies. So, the name of the game is to avoid engine operation at rpms which excite propeller resonances and thus maintain propeller stresses below the allowable level.

One distressing problem is the fact that there may be no physical evidence of the amount of life remaining in a propeller. When as much as 90 percent of a blade's life has been used up, it has been shown to be impossible to detect any abnormality with the best available inspection techniques. For this reason, when obtaining a metal propeller, it is wise to start with a new one of known condition.

Much has been written about detecting metal fatigue through inspection for cracks. This should not give the false impression that the absence of cracks indicates that there is a large amount of life remaining in a propeller. It could fail on the very next flight. Wood, however, does not have this wear out characteristic.

WHY USE METAL

If wood is such a good material for propellers, why should anyone ever make them from aluminum alloy? They shouldn't — except for applications where performance is important. And then there are the applications where wooden propellers haven't been able to hold together.

Wood has some very desirable characteristics, but it is simply not as strong as dural. Wooden propeller blades must be made thicker than metal blades to withstand load stresses and maintain stability to prevent flutter. Wood is weak in torsion and may disentegrate in violent flutter if the blade is not made strong enough. The thinner metal blade is more efficient at high speed. Metal blades can be run efficiently up to tip speeds of Mach .85 to .9 while wood blades are limited Mach .72 or .74. Henry Rose, Chief Engineer at Sensenich Corporation, which builds both wooden and metal propellers, says that metal propellers are at least 10% more efficient. One striking example was a Stinson 108 which was test flown for 50 hours with both a 2-position wooden propeller and a fixed pitch metal propeller. While cruising at the same airspeed, with the metal propeller, there was a 25% increase in flight time on a tank of fuel.

Suppose you are willing to accept the performance penalty, are there any other reasons for using metal? If your engine is a large Lycoming flat four (0-290 thru 0-360) the answer is yes.

First, the crankshaft flange on these engines is an SAE-2 type which is not adequate to transmit the engine impulses to a wooden hub. A type 3 or 4 flange would be required. Suppose you make a suitable adapter, then what? Then all you need to do is find someone who can make a wooden propeller which will hold together on these

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engines. Two wooden props were tried on T-18s and one four-blade version on the 0-290 powered Mini Mustang. All three, although made by a reputable homebuilt propeller manufacturer, came apart at the seams, apparently due to glue failure.

FLIGHT TESTING COSTS

If your airplane can use a standard unmodified certificated propeller, there is no problem, but, if you need a propeller cut down below approved minimums, you are probably playing Russian Roulette. For this reason, the two fixed-pitch metal propeller manufacturers in the United States have refused to sell cut-down propellers. The problem is that the price tag on an in-flight vibration analysis is about $10,000 for each powerplant-propeller combination tested, and there is no other absolute means to determine the safe rpm operating range for a metal propeller.

It should be understood that there are two reasons that it might be desirable to use a propeller with less than the 74 to 76 inches commonly available in FAA certificated configurations. First is the very serious matter of ground clearance. Although the standard 9 inch clearance required for type certificated aircraft is not a requirement for homebuilts, there is a practical limit to the amount of deviation which can be tolerated. For instance, a design which required a 60 in. long prop just couldn't use a prop 74 in. long. Seven inch long gear extensions would be a bit cumbersome. The second consideration is propeller efficiency. The optimum diameter decreases with increased speed and increased rpm. A 68 inch long propeller is optimum at 2850 maximum rpm and 200 mph.

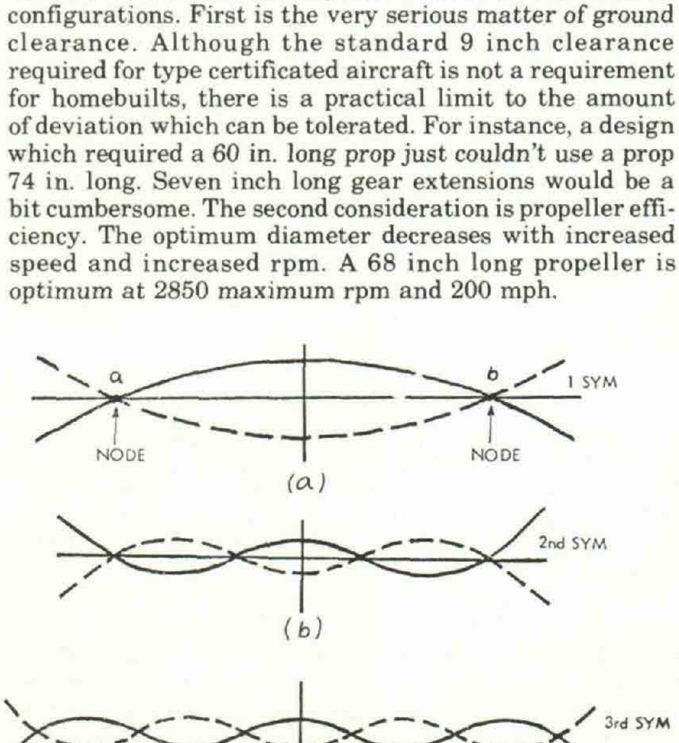


Figure 2 Symmetrical Bending Modes

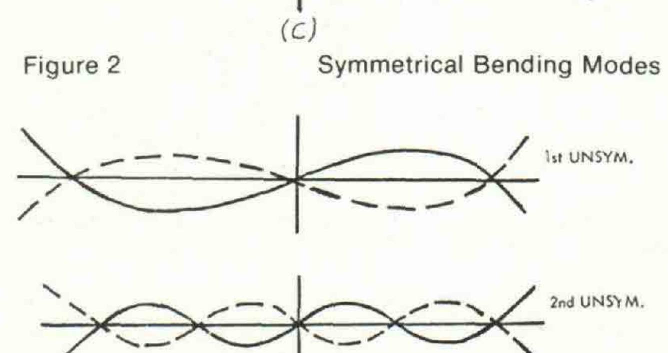


Figure 3 Unsymmetrical Bending Modes

ARE METAL PROPS SAFE?

When properly designed, maintained and used, metal propellers are perfectly safe. Otherwise, they are almost certain to come apart. To explain why requires that we define some technical terms and use some graphs and equations. If you are not technically inclined, stick with us because you will be able to grasp the important parts without completely understanding all the details.

As mentioned earlier, all propellers vibrate while in motion. Tap the tip of one (gently) and it will ring like a tuning fork. The tip vibrates back and forth a certain number of times per second. A 76 EM Cherokee propeller, when not rotating, will vibrate about 60 times per second when struck. We say its natural frequency is 60 cycles per second (cps). The only problem is that a propeller, like any piece of metal doesn't just want to vibrate at one frequency, but many different frequencies. The reason for this is illustrated in Figure 2 which shows a long slender uniform beam under vibration. When the beam flexes so that it has just one bend (Figure 2a) we say that it is vibrating in the *first bending mode*. Notice that points a and b remain stationary and do not move linearly back and forth. These two points are called *nodes*.

Now, the beam also will bend twice as in Figure 2b. This is the *second mode*. Notice that there are four nodes. Figure 2c shows the third mode with 6 nodes. Higher modes are also present, but they are usually unimportant and can be ignored. Figure 2 illustrates bending where the tips are vibrating symmetrically in phase. When they are out of phase, as shown in Figure 3, it is called unsymmetrical bending.

Each bending mode occurs at a different frequency. If the beam is caused to oscillate with some external driving force, as the frequency of the oscillation is increased from zero, when the first natural frequency is reached, the beam will vibrate with a much larger amplitude. This is called *first mode resonance*. At some higher frequency the second mode resonance will occur and, at a still higher frequency, the third mode resonance will be encountered.

The natural frequencies of a propeller can be readily determined experimentally by suspending it horizontally on a shock cord and shaking it with a variable speed shaker at the hub. See Figure 4. When resonant points are reached, the propeller tips can be seen visually to vibrate. Frequency is measured with a strobotac.

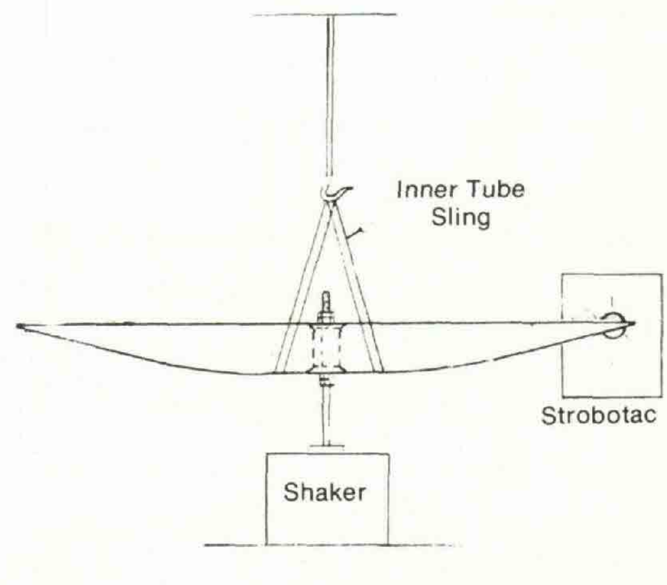


Figure 4. Static Shake Test

Nodal points can be located by sprinkling sawdust on the blade or running a pencil tip lightly along the blade at the 40% chord point until it stops vibrating. The shaker can be an electromagnetic device or simply a pneumatically operated drill with an eccentric mass attached. This produces symmetrical bending which is more important for the present analysis.

Now enter the real driving force, torque impulses from the engine. In a typical four cylinder engine there are two firing pulses per revolution. To complicate the situation, integer multiples of the fundamental torque pulses must be considered as driving disturbances (2N, 4N, 6N, 8N and 10N). But this wouldn't be too complicated if the propeller didn't need to rotate. When the blade spins, centrifugal forces make it appear stiffer and all the bending mode natural frequencies increase. Fortunately, there is a simple equation which can be used to convert the static frequencies to rotational frequencies. It is:

$F_r^2 = F_o^2 + CN^2$ and by definition $F_r = PN$
F_r = rotating frequency in cycles per minute
F_o = static frequency in cpm
N = engine rpm
C = coefficient for each mode
P = the order of the vibration
(for sym. mode 1, $C = 1.5$; mode 2, $C = 4.5$; mode 3, $C = 9$)

The above coefficients have been determined by Henry Rose for Sensenich props with 1.25" solid disc extension, and are valid *only* when the static data is taken with the propeller removed from the engine and suspended on a bungee.

It is common to plot two families of curves to examine the resonant points under rotating conditions. See Figure 5. The first set are hyperbolas showing the relation between the natural frequencies of a blade in its various modes and the speed of rotation as expressed by the above equation. The second set are straight lines emanating from the origin, expressing the relationship between the exciting frequency and the speed. These straight lines have slopes equal to the order of the driving excitation (2, 4, 6, etc.). Any intersection of one of the straight lines of exciting frequency with one of the curves of natural frequency indicates a resonant point. These resonant points can be found directly by rearranging the equation as follows:

$N^2 = F_o^2/(P^2 - C)$ where P is the order of excitation (2, 4, 6, 8 and 10) and $PN = F_r$.

Now, in case you are lost, let's work an example problem to show how simple it really is. When a 76 EM propeller cut down to 70 inches with 72 inches of pitch was vibrated, the following data was obtained:

MODE	F_o	Node Location from tip
1.	4,329 cpm	17"
2.	13,438 cpm	5.75" and 23.25"
3.	26,097 cpm	3½", 13" and 25"

Table I Static Vibration Data

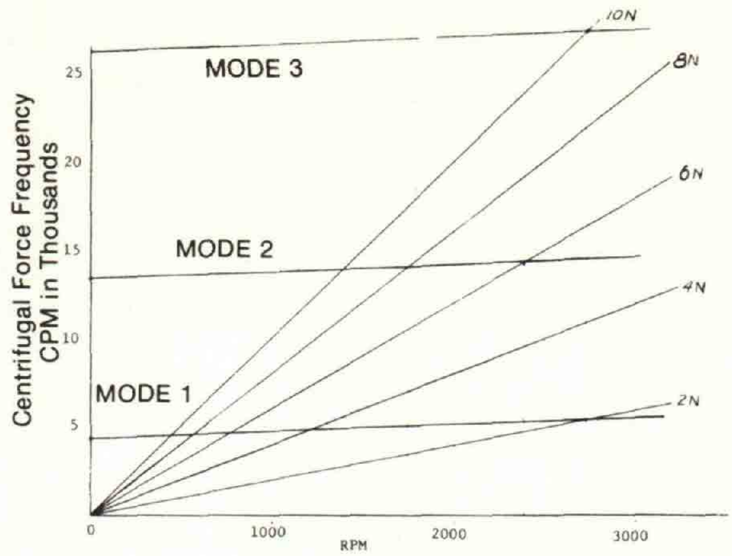
Solving for: 1st mode 2nd order resonance,

$$N = \frac{4.329}{\sqrt{2^2 - 1.5}} = 2738 \text{ rpm}$$

2nd mode 6th order, $N = \frac{13{,}438}{\sqrt{6^2 - 4.5}} = 2394$ rpm

3rd mode 10th order,

$$N = \frac{26{,}097}{\sqrt{10^2 - 9}} = 2736 \text{ rpm}$$



Predicted Resonance Speeds
For Engine-Propeller Combination

Figure 5

Other data for this propeller, an early model Sensenich M76 EMMS-6-73 serial number 44570, is shown in Figure 5. As a general rule, static mode 2 frequency is 3 times mode 1, and mode 3 is 2 times mode 2. When 2 inches length is cut off a propeller, it shifts all frequencies upward about 100 rpm. Let us now see how the predicted resonances check out in actual flight tests.

IN-FLIGHT VIBRATION SURVEY

After only 30 hours of flying time on a cut-down M74-6 propeller, Bob Dial, a General Motors corporate pilot, had a blade failure 17 inches from the tip. The blade did not separate, however, and he got down safely. Following this incident, Bob arranged with Hartzell Propellers to conduct a full fledged in-flight vibration survey using his 0-320 Lycoming powered T-18 as the test vehicle. Two different propellers and three crankshaft extensions were tested in a total of 23 flights. The propellers had a number of strain gauges attached along the front face to measure stresses and electrical signals were fed through a slip-ring assembly to 475 pounds of test equipment and recorders. Static vibration tests were also done providing the data shown in Table I.

Figure 6 is a plot of stresses at the 15 inch point (1st mode node) and the 5" point (2nd and 3rd mode nodes) taken during flight at full throttle with rpm controlled by airspeed. Note that stresses for the first mode are a maximum (peak) at 2780 rpm compared to the predicted 2738. The third mode peaks, measured at 5" from the tip, are at 2610 compared to 2736 predicted. A small peak occurred at 2390 compared to a second mode prediction of 2394. The only significantly high stress was due to the 1st mode which exceeded the allowable level by over 2000 psi. Notice that the stresses above 10,000 feet altitude are 75 percent higher than below 5000 feet. This is because the air is much thinner at high altitude and provides less damping. Hartzell recommends that this propeller be restricted to 2550 rpm above 5,000 feet with no rpm restriction below 5,000.

Tests on the M74 propeller cut to 68 inches length showed stresses far in excess of the allowable limit at 2630 rpm. Bob Dial cruised right at that rpm, usually at high altitude, which explains his blade failure. This propeller is now restricted to 2500 rpm at all altitudes.

These tests are extremely significant to builders of homebuilt aircraft. First, it shows that a relative inexpen-

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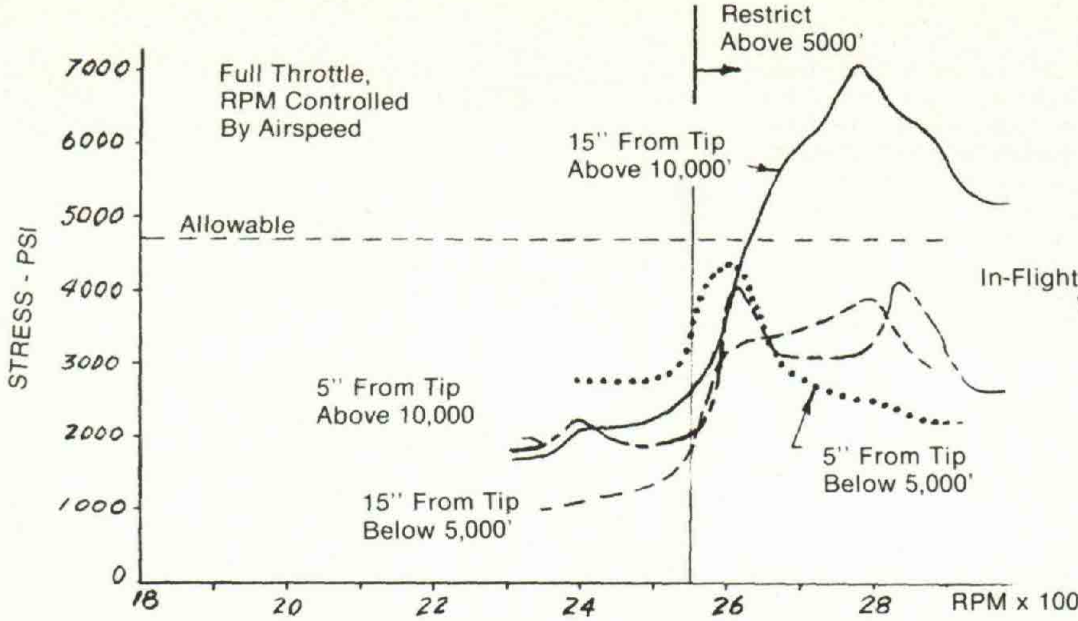

Figure 6

In-Flight Data on 76EMMS-6-73 Prop With 1072 Extension

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sive static shake test can be used to fairly accurately predict in-flight resonant frequencies although it doesn't indicate actual stress levels. Second, test data is now available on two reduced diameter propellers for large four cylinder Lycoming engines and three crankshaft extensions. (From the author for $2.00).

Hartzell charged only a nominal amount for the tests which was paid through donations almost exclusively by T-18 builders. Dave Biermann, Hartzell president, and other members of his staff deserve a hearty vote of thanks for this contribution to the safety of homebuilt aircraft.

NEW PROPELLER AVAILABLE

As a result of this testing program, Sensenich Propellers of Lancaster, Pa. 17604 has agreed to supply a special metal propeller for the 0-290 through 0-320 series Lycoming engines. It will be efficient for use on aircraft with maximum speeds in the range between 170 to 200 mph. Its designation is 76EM6-8-XX. It is the current model 76 EM propeller cut to 68 inch length. The 6 means six sixteenths size attaching bolts (⅜"). Pitch will be made to order (the last 2 digits) up to 74 inches. It is not approved for use on the 0-360 engine because the 76 EM blank originally has 60 inches pitch and they consider it unsafe to twist it to the over 80 inch pitch needed for the 0-360. Furthermore, the higher engine impulses coupled with the much lower frequency of the crankshaft torsional mode of this engine makes it unsuitable for use with a shorter than standard 76 EM propeller. The new propeller will be available only through direct purchase from the factory. This is the third special metal propeller offered by Sensenich. The other two are the 54EK-O-XX Formula I Racing Propeller with a green range *only* between 3500 and 4000 rpm and the 64DM6-0-XX for 0-290 Lycoming powered biplane racers with a green range *only* from 2800 to 3300 rpm. The only option on these propellers is pitch. The placard on rpm is absolutely *fixed*. No other length is available. Each propeller is supplied with a data sheet specifying speed placards.

The new propeller will be made 68 inches long because the new 76 EM blank is thinner than the old 76 EM prop which Bob Dial had tested. The new standard length 76 EM is distinguished by a K following the serial number. All resonant frequencies of this propeller are 90 rpm below those for the 76 EM propellers without a K following the serial number. The first mode (rotating) for the full length 76 EM is 225- rpm and 2160 for the K model. So the new 68 inch propeller will have virtually the same resonances as the 70 inch one Hartzell flight tested.

Blade pitch, engine mounts and other mechanical parts of an airplane affect propeller resonances, but they are relatively unimportant compared with blade shape and length.

SAFETY STRAP

Since even the best designed metal propeller occasionally sheds a blade due to fatigue cracks emanating from the inevitable stone damage, it might be wise for all homebuilts with metal propellers to have safety straps attached between fuselage and engine. Early propeller manufacturers found this practice valuable on experimental installations to keep the engine from separating from the aircraft in case of propeller failure. Formula I racers now are required to have such a strap installed. Use a heavy piece of steel cable of sufficient excess length to allow several inches free play.

LOW COST TESTING SERVICE

Anyone using a cut-down metal propeller who is not equipped to perform the static shake tests outlined in this article can send or take a propeller to Specialized Testing Service, 10758 Burbank Blvd., North Hollywood, California 91601 where Sandy Friezner will perform the tests and prepare a data sheet showing possible resonant rpm's. The cost of this service is only $25. This type of test does not produce results which have the same precision as those obtained from an in-flight survey, but they are far better than none at all.

EFFECTS ON AIRPLANE DESIGN

Henry Rose stresses the importance of considering propeller restraints when the design for a new aircraft is formulated. The propeller is sometimes ignored until too late and the propeller designer is stuck with an impossible problem. This is even more important in the case of a designer of homebuilt aircraft who cannot guarantee sufficient propeller sales volume to justify a new propeller development. If you are a potential builder evaluating various possible designs, the availability of a suitable propeller should be one of the most important factors influencing your selection. The application of metal propellers is definitely not a matter of seat-of-the-pants engineering.

One of the best available discussions of this subject appears in FAA Advisory Circular 20-66 dated 1/29/70 entitled "Vibration Evaluation of Aircraft Propellers". All designers of propeller driven homebuilt aircraft are urged to read this document available from: Dept. of Transportation, FAA, Distribution Unit TAD-484.3, Washington, D. C. 20590.