Sept. 6, 1960 F. L. STULEN ET AL 2,951,542

BALANCE AND TRACKING OF ROTOR BLADES

Filed Oct. 21, 1957

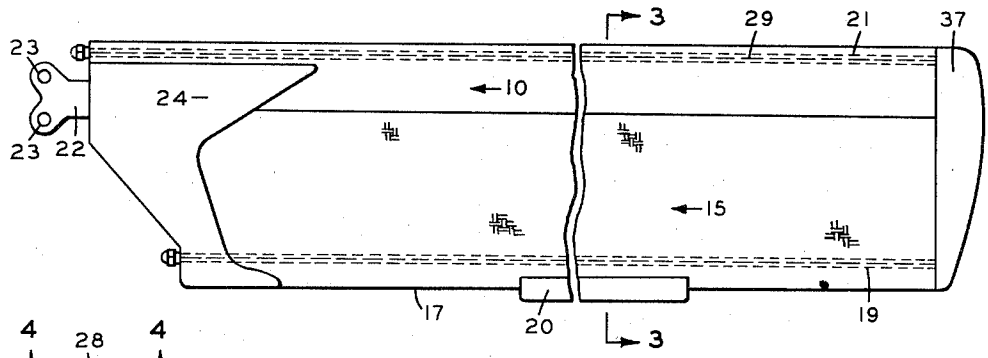


FIG. 1

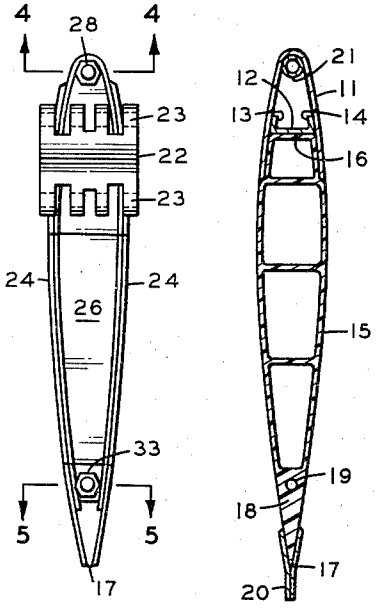


FIG. 2

FIG. 3

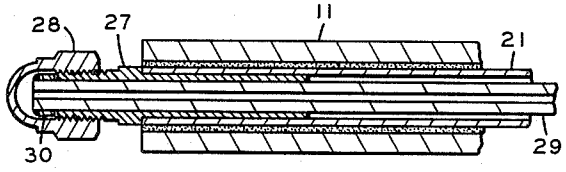


FIG. 4

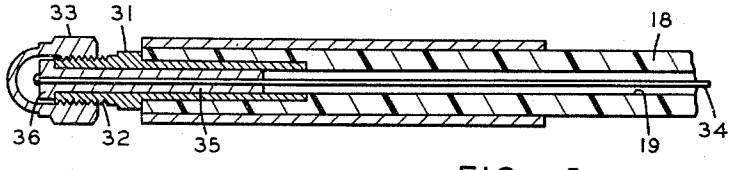


FIG. 5

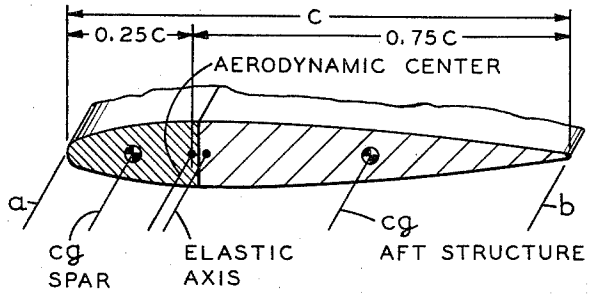


FIG. 6

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United States Patent Office 2,951,542
Patented Sept. 6, 1960

2,951,542

BALANCE AND TRACKING OF ROTOR BLADES

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Filed Oct. 21, 1957, Ser. No. 691,190

8 Claims. (Cl. 170—159)

This invention relates to the manufacture, balance and tracking of rotor blades for helicopters and the like. Its objects include matching the performance of rotor blades which make up a set, and also matching blades to a standard whereby to achieve interchangeability. More detailed purposes will be apparent from the discussion which follows.

The matching of performance characteristics of rotor blades has been one of the most persistent problems of the helicopter industry. Individual differences between rotor blades in their response to dynamic and aerodynamic forces, and deflections in bending and twisting under these forces, can cause serious difficulties, including roughness in operation and control.

To match as closely as possible the performance of the blades which constitute a set, they are usually "tracked" together. It is conventionally considered sufficient to achieve substantial correspondence merely in the tip paths of the several blades being tracked with each other; this is conventionally done by adding chordwise-adjustable tip weights.

The phenomena involved are complex and difficult and the solution proposed by the prior art cannot be summarized in any simple statement. In a very general way, it may be stated that according to the prior art, blades are individually balanced according to the designer's favorite criteria, and then tracked to each other, in sets of two or three, utilizing either a whirl test stand or the rotorcraft itself. It has not heretofore been thought possible to mass produce blades which are preliminarily balanced to a chosen mass distribution and which may be used interchangeably in sets by a simple tracking procedure whereby the master blade's aeroelastic performance is closely approximated.

One cause of difficulty in the prior art has been the use of concentrated weights interposed at various points along the blade for the purpose of achieving better track. Shifting of such concentrated weights from one point to another may achieve one good effect but have a secondary bad effect. For instance a concentrated weight which does not lie on the elastic axis of the blade tends to twist the blade as the blade flexes. Such twisting will be cyclic, resulting in cyclic variations in the air load distribution which have secondary effects on the relatively elastic blade structure. This is a highly simplified example of one aeroelastic effect which follows from spanwise discontinuity in mass distribution of such shiftable concentrated tracking weights.

In contrast to this conventional tracking procedure, the present invention importantly lessens the need for (and extent of) blade tracking, both by providing structure and a preliminary balancing which obtains a substantial station-by-station correspondence in blade properties. Use is made of blade structure designed for minimum variation in spanwise elastic properties, mass distribution, and center of gravity; and provision is made for bringing each blade up to a uniform standard weight and balance without disturbing the spanwise mass distribution. The factors which give rise to the need for tracking are thus minimized. The invention further provides for tracking by utilizing one-piece leading edge and trailing edge full span balances. Initially, blades are brought up to the standard weight and are balanced at a pre-selected chordwise position near the aerodynamic center. Subsequently this position may be adjusted to remedy such tracking deficiences as the individual blade may exhibit. The standard weight is kept to a value less than the total weight of a theoretical blade made up of parts which individually were of the maximum permissible weight.

Stated somewhat more specifically (but without limiting the detailed description which follows) the present invention teaches how to construct blades which are matched to a "master" or standard blade in all significant respects. It teaches providing a blade with structural elements which extend continuously, full span, from root to tip—such as a leading edge spar and an aft structure including a trailing edge—with spanwise hollow tubes along the inside of their leading and trailing edges at the level of the chord plane, as shown. The invention also teaches securing within each tube a full span balance, which may itself be a tube or a solid rod which fits closely within one of the first mentioned tubes. Using a trailing edge balance weight represents a novel step to providing standard blade characteristics. In combination with the other features and method steps taught, each blade, mass produced out of material subject to normal tolerances, will have the same weight and substantially the same mass distribution as the master blade; also a similar distribution of elastic characteristics such as bending and torsional stiffness and response to periodic forces. As a result, the aeroelastic responses of the blades may be also readily standardized; and for this purpose the present invention teaches how to select and use a pair of such full span balances in the leading and trailing edges of each blade to achieve balance with the master blade of weight and mass moment at all stations (i.e. cross sections) along the span. The invention also teaches how to use the same two fixed positions for balances in the final tracking of the blade so that it will perform like the master blade in flight, preserving in such final tracking a spanwise continuity of the blade properties which affect its flying qualities and avoiding the aimlessness of prior art tracking.

In the accompanying drawings:

Figure 1 is a plan view of a rotor blade embodying and made according to the present invention, shown somewhat schematically;

Figure 2 is an enlarged left end view of Figure 1;

Figure 3 is an enlarged sectional view taken along line 3—3 of Figure 1;

Figure 4 is a further enlarged fragmentary section taken along line 4—4 of Figure 2;

Figure 5 is a similarly enlarged fragmentary section taken along line 5—5 of Figure 2; and

Figure 6 is a diagrammatic sketch of a hypothetical rotor blade referred to as illustrating the method of the present invention.

The rotor blade shown comprises a leading edge spar generally designated 10 which extends full span from the blade root to the blade tip. Such spar 10 comprises the principal structural member of the blade and may be made up of a continuous steel, curved leading edge plate 11, and a vertical channel 12 likewise full span and having upper and lower flanges 13, 14 brazed within the upper and lower inner surfaces of the plate 11. The steel sheet material for the leading edge plate 11 and channel 12 is commercially furnished not to a precise thickness but within a range of commercial tolerances, which accounts for a variation in weight as between one piece of sheet or plate and another. However, there

is relatively little variation in the thickness of any single sheet or plate from one end to the other. Hence, by fabricating the spar **10** so that its principal member extends full span, without intermediate chordwise members between the root and tip, there is little variation spanwise in the mass distribution of the spar **10**.

While the aft structure may likewise consist of metal sheet elements running the entire span, there is here shown plastic molded aft structure generally designated **15**, and is molded of fiberglass fabric and resin, as hereafter described, the fiberglass consisting of sheets each extending from the blade root to the blade tip. As with steel sheets, substantial weight variation does not exist within a single piece of the cloth. We use familiar manufacturing controls to assure an even distribution of the resin plastic. In the aft structure **15** the spanwise mass distribution is thus kept substantially constant along the span.

The aft structure **15** consists of a spanwise reinforced shell molded of fiberglass cloth and plastic resin to the airfoil contour, and having a nose portion **16** fitted between the aft edges of the leading edge plate **11** and against the aft side of the channel **12**, and terminating in a trailing edge **17** reinforced by a pre-molded plastic triangular insert **18** having a full span cylindrical hollow **19**. A simple ground adjustable metal trim tab **20**, bonded over a portion of the trailing edge **17**, is added for matching the blades aerodynamically.

Brazed or tack welded inward and closely adjacent the leading edge plate **11** is a full span leading edge tubular receptacle **21** whose inner surface is cylindrical, preferably a thin-walled tube. This receptacle **21** serves a function similar to the trailing edge cylindrical hollow **19**, as hereafter described. At the root, the blade is provided with a retention fitting generally designated **22** having bores **23** for mounting to the blade hub. The retention fitting **22** is shown somewhat schematically. The blade may further have upper and lower root reinforcement plates **24** extending rearward chordwise to grasp the trailing edge **17**. Preferably the root portion of the blade aft of the spar is closed by a root rib **26**.

Figure 4 is taken through the root end fragment of the leading edge receptacle **21**, in the root end of which is rigidly affixed a receptacle bushing **27** projecting inward from the spar **10** toward the rotor hub and externally threaded to receive a cap nut **28**. Inside the tubular receptacle **21** is inserted a full span, leading edge mass balance **29**; which in the embodiment shown is a hollow tube. The outer wall of the tube which comprises the mass balance **29** fits fairly close to the inner wall of the cylindrical receptacle **21**, so as to bear against it when the blade is subjected to the bending deflections normally encountered in flight. Such bending deflections are so great, compared with the clearances, that much of the centrifugal load due to the mass balance **29** is resisted in friction along the cylindrical inner wall of the receptacle **21**. Positive security is afforded by brazing the inner end of the leading edge mass balance **29** within a retaining collar **30** which bears against the end of the receptacle bushing **27**, and by enclosing the retaining collar **30** within the cap nut **28**. If desired, a full span solid rod or wire may be substituted for the hollow tube which serves as the leading edge mass balance **29**.

Along the trailing edge a somewhat similar provision for balance is made, with details designed for lighter weight. As shown in Figure 5, the full span cylindrical hollow **19** in the trailing edge **17** is fitted at its root end with a bushing **31**, fitted and bonded within the pre-molded triangular insert **18**, and having an externally threaded projecting end portion **32** fitted with a cap nut **33**. Within the cylindrical hollow **19** is provided a trailing edge mass balance wire **34** extending the full span of the blade, and brazed at its inner or root end within an axially drilled retainer **35** having a head **36** which abuts the outer end of the bushing **31** within the cap nut **33**. As illustrated, the leading edge mass balance tube **29** and trailing edge mass balance wire **34** are secured within their respective tubular receptacles **21**, **19** at their root ends only. The tube **29** and wire **34** are omitted from Figure 3.

The tip end of the blade structure may be closed with a tip fairing **37**.

Figure 6 is included to illustrate the method of the present invention. The utilization of full span sheet material elements for both a spar and an aft structure, without any substantial members intermediate the blade root and the blade tip, results as follows: the centers of gravity of each spanwise member, taken at successive stations along the span, will lie along straight spanwise axes, shown in the typical schematic section of Figure 6 as "*cg* spar" and "*cg* aft structure." For simplicity these are shown midway between the aerodynamic center and the leading edge and trailing edge respectively. The leading edge tubular receptacle **21** likewise has a straight spanwise axis, designated *a* and shown here as lying at the front of the leading edge; and the trailing edge cylindrical hollow **19** has a similar axis *b*, shown here at the aft margin of the trailing edge. The aerodynamic center of the section is assumed to lie at the 25° chord point.

The weight of the root retention is neglected in this hypothesis, and the blade is considered as being made up of a spar and an aft structure. If every sheet element which makes up these structures is of maximum thickness, their total weight would be the maximum, taken here as 100 lbs. A commercial thickness tolerance of 8% is assumed, making the theoretical minimum weight of the blade 92 lbs. Of such total maximum weight, the spar may range from 69 to 75 lbs., while the aft structure may range from 23 to 25 lbs.

Let us assume that a blade assembled of two such spanwise-extending parts, each weighing precisely a standard weight (chosen at a certain percentage of a standard tolerance) balances along an axis coincident with the aerodynamic center, without added weights. Then, such balance will also be achieved without added weights if both components are of the maximum weight, and likewise if both components are of the minimum weight, without any added weights in the leading edge or trailing edge. There is, statistically, little likelihood that any one of these combinations will occur in routine manufacture.

Assuming the unlikely combination that the spar is at its maximum weight of 75 lbs. and the aft structure at its minimum weight of 23 lbs., a 1-lb. mass distributed along the entire spanwise trailing edge axis *b* will balance the blade at its aerodynamic center. This unlikely combination results in a total weight of 99 lbs., instead of the 100-lb. weight if both components were of the maximum possible thickness. If the aft structure were its maximum weight of 25 lbs. and the spar at its minimum weight of 69 lbs., a weight of 3 lbs. added along the leading edge axis *a* would balance the blade at the aerodynamic center and bring the total weight to 97 lbs. If each component is of average weight, the combination would balance at the aerodynamic center without added weight, and such combination would weigh 96 lbs.

Applying the laws of probability to the assembly of these two components, only a very small percentage of blades to be assembled could exceed an arbitrarily selected weight of say 98 lbs. This figure may be selected as the standard weight for such a blade. Although a statistically few blades may be assembled which cannot be balanced at the aerodynamic center at such a weight, such few blades may be either rejected or balanced at a slightly higher weight. Alternatively, rather than assembling parts at random, parts may be first weighed and then selectively assembled so that their weights total less than the standard blade (for example, by using only one above-average-weight part per assembly), and prac-

tically all blades so assembled will be found to be balanceable at the standard weight.

The details of procedure for balancing may be varied; but the method is essentially as follows: The mass moment of a blade of standard weight and assumed standard properties is first determined in reference to a spanwise axis, which may be either the leading edge receptacle axis *a* or the trailing edge receptacle axis *b*. This figure is used as a standard mass moment about such axis. It will normally exceed the mass moment of the assembled production blades. Each production blade is brought up to a corresponding mass moment about its corresponding axis. A simple means of so doing is to suspend each blade so that it may rotate about such axis, measure its mass moment thereabout, and then add a spanwise-distributed weight along the axis through the hollow at the opposite edge, sufficient in amount that its mass moment about the first axis remedies its deficiency in mass moment as compared with the standard mass moment about such axis.

Into the hollow about whose axis the mass moment was taken, there is then inserted a sufficient spanwise-distributed weight to bring up the weight of the blade to the standard weight. This will also serve to fix the center of gravity of the blade at the same chordwise location as in the standard blade. This line may advantageously correspond to the aerodynamic axis of the blade, especially if the elastic axis of the blade does not depart materially therefrom.

Such balanced construction will be found substantially to lessen the need for tracking of blades. Final tracking may be by the use of small but otherwise conventional tip weights, if desired. However, without using such tip weights, the blades may be tracked, preferably with a chosen standard blade, on a whirl test stand, using the following procedure:

With the blades in flat pitch, the trim tab **20** of the production blade is bent and any pitch link thereon is adjusted until satisfactory tracking is obtained. The production blade is then considered as aerodynamically similar to the standard blade. The manner of construction described yields, in addition, similarity as respects mass moment and center of gravity at each station along the span.

Despite these similarities, individual blades will exhibit some variation in performance characteristics, due perhaps to differences in elastic characteristics. In order to remedy these variations, the combined weight of the particular leading edge mass balance **29** and trailing edge balance wire **34**, which brought the particular blade to balance at master weight, is first noted. These balances are removed, and for them substitution is made, experimentally, of other pairs of spanwise-extending masses, whose total weight equals their total, but one mass being slightly heavier and the other slightly lighter. The blades are again whirled and the track of the production blade as against the standard blade is compared over a desired range of pitch angles, the experimental substitution being continued until satisfactory tracking is achieved.

The weight of the leading edge mass balance **29** may be varied by choosing a tube of different inner diameter without affecting its clearance within the leading edge receptacle **21**, or by using a full span rod or stiff wire. Similarly, for the balance wire **34** there may be substituted in the trailing edge cylindrical hollow **19** any other full span mass which may be accommodated therein.

The success of this procedure in obtaining good track is thought to be explainable as follows: Where there is a departure in fact between the elastic axis and the aerodynamic center, as shown in Figure 6, the change of the division of weight between the full span balances without changing the total weight in effect tunes the dynamic and aerodynamic characteristics of the individual blade, adjusting the position of the center of gravity chordwise

at each station along the span to an axis which the tracking procedure itself has proved to be the best center of gravity location for the particular blade. The effects on blade twist of centrifugal forces due to chordwise distribution of masses, have thus aided in achieving tracking; no isolated masses can cause undesirable dynamic, aerodynamic and aeroelastic effects; and the master weight of the blade is maintained.

Utilizing the structural principles here described and the methods of obtaining balance and tracking, there is achieved a rotating blade wherein each airfoil portion, section by section, is in substantial trim with the aerodynamic, static and dynamic forces for which it itself is responsible. This enables the mass production of interchangeable blades, weighing less than the maximum predicted weight for the material, and possessing a uniformity of performance characteristics not heretofore achieved.

When used in the claims, the term "full span" is to be understood as meaning the blade span length less such length as may be provided for fittings, fairings and attachments at the root and tip.

We claim:

1. A rotor blade comprising blade structure composed of constant gauge sheet material elements extending spanwise and uninterrupted between the blade root and tip, tubes inwardly adjacent both the leading edge and the trailing edge of the blade, balances within the said leading edge and trailing edge tubes, each of said balances extending from the blade root to the tip and means for removably mounting said balances within said tubes, whereby the total weight of said full span balances may be allocated between the said tubes.

2. A rotor blade as defined in claim 1, the leading edge tube being cylindrical, the balance therein being a tube whose outer diameter fits closely inward of the inner diameter of the leading edge tube.

3. A rotor blade characterized by spanwise continuity of structure and mass balance, comprising a full span leading edge part having a full spanwise-extending hollow inwardly adjacent the chordwise forward portion thereof, a full span aft part having a trailing edge and a full spanwise-extending hollow inwardly thereadjacent, a full span leading edge balance mounted within said leading edge hollow, and a full span trailing edge balance mounted within said trailing edge hollow, each of said balances having a spanwise-extending axis.

4. A rotor blade characterized by spanwise continuity of structure and mass balance, comprising a root retention fitting, a leading edge part secured at its root end thereto, said part including full span sheet material and having a full spanwise-extending tubular hollow inwardly adjacent the chordwise forward portion thereof, an aft part including full span sheet material and having a trailing edge and a full spanwise-extending tubular hollow inwardly thereadjacent, a rod-like, full span leading edge balance mounted at its root end within said leading edge hollow with its outer surface fitting closely within the inner surface of said hollow, a rod-like, full span trailing edge balance mounted at its root end within said trailing edge hollow with its outer surface fitting therewithin, each of said rod-like balances having a spanwise-extending axis.

5. The method of selectively assembling and balancing a rotor blade about a spanwise axis and simultaneously increasing the weight to correspond to the balance and weight of a similar standard blade, comprising the steps of selecting for assembly, parts including a leading edge spar and a strailing edge structure whose weights total less than those of such standard blade, then assembling the blade including said selected parts, then selecting and inserting within one of said parts, adjacent its edge, a full span mass sufficient to increase the mass moment of said blade about a spanwise axis within and adjacent the edges of said other part to a value equal to the mass moment of such a standard blade about its corresponding

axis, and then selecting and inserting into said other part along the said axis within its edge a substantially full span mass sufficient to bring the total weight up to that of such standard blade.

6. The method of balancing a rotor blade about a spanwise axis and simultaneously increasing the weight thereof to correspond substantially to the balance and weight of a standard blade, comprising the steps of inserting in a spanwise hollow having an axis inwardly adjacent a first edge of said blade, a spanwise-extending mass sufficient to increase the mass moment of said blade about a second spanwise axis inwardly adjacent the other edge thereof to a value equal to the mass moment about such second axis of such standard blade, and then inserting in a hollow along such second spanwise axis, a spanwise mass sufficient to bring the total weight up to that of such standard blade.

7. The method of balancing and tracking a rotor blade whereby to bring its performance into close correspondence with that of a blade selected as a standard blade, comprising the steps of inserting in a spanwise hollow having an axis inwardly adjacent a first edge of said blade, a first spanwise-extending mass sufficient to increase the mass moment of said blade about a second spanwise axis inwardly adjacent the other edge thereof to a value equal to the mass moment about such second axis of such standard blade, then inserting in a hollow along such second spanwise axis, a second spanwise mass sufficient to bring the total weight up to that of such standard blade, then whirling the blade together with the standard blade and trimming it aerodynamically to track with the standard blade at substantially flat pitch, and then whirling it with the standard blade at various pitch angles and experimentally substituting for said first and second spanwise masses other pairs of spanwise-extending masses whose total weight equals the weight of said first and second masses, until optimum tracking with such standard blades is obtained over a desired range of pitch angles.

8. The method of blancing and tracking a rotor blade whereby to bring its performance into close correspondence with a standard, comprising the steps of inserting in a spanwise hollow having an axis inwardlly adjacent a first edge of said blade, a first spanwise-extending mass sufficient to increase the mass moment of said blade about a second spanwise axis inwardly adjacent the other edge thereof to a value equal to a standard value, then inserting in a hollow along such second spanwise axis, a second spanwise mass sufficient to bring the total weight up to a stadard weight, then whirling the blade and trimming it aerodynamically to track at substantially flat pitch, and then whirling it at various pitch angles and experimentally substituting for said first and second spanwise masses other pairs of spanwise-extending masses whose total weight equals the weight of said first and second masses, until optimum tracking is obtained over a desired range of pitch angles.

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