(54) Title: ROTOR SPEED MANAGEMENT

(57) Abstract: A flight control system for a rotorcraft includes a controller configured to receive input indicative of ambient conditions, determine a threshold rotor blade tip speed based on the input, and to output rotor control commands to prevent rotor blade tips from exceeding the threshold speed. An aircraft includes an airframe, a main rotor assembly operatively connected to the airframe, and a flight control system as described above. The flight control system is operatively connected to control the main rotor assembly. It is contemplated that the main rotor assembly can be a counter rotating coaxial main rotor assembly including an upper rotor assembly with a plurality of blades and a lower rotor assembly having a plurality of blades, wherein the flight control system is operatively connected to control both upper and lower rotor assemblies to prevent any blade tips of the upper and lower rotor assemblies from exceeding the threshold speed.
ROTOR SPEED MANAGEMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application no. 62/058,424 filed October 1, 2014, the contents of which are incorporated by reference herein in their entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present disclosure relates to aircraft control systems, and more particularly to flight control systems such as used in controlling rotors of rotorcraft.

2. Description of Related Art

A limiting factor on the rotor of rotorcraft is the sound barrier. The effective air speed at any given point on a rotor blade in motion is a function of the rotational speed, the radius to the point of interest from the center of rotation, and the forward flight speed of the rotorcraft. The further away from the center, the greater the effective air speed at that point on the rotor blade. The tip of the advancing rotor blade therefore has the highest effective air speed when the rotor is operating at high rotational speed and high forward flight speed. If the rotational speed is high enough, the tips of the rotor blades will exceed the sound barrier and the air flow at the tips will transition from an incompressible regime to a compressible regime. Typical blades are designed to operate efficiently only in the incompressible regime of fluid dynamics, and do not perform as efficiently in the compressible regime. At high rotational and forward flight speeds, as the blade tips exceed Mach 1.0, the advancing blade tips can precipitously lose lift and/or experience increased drag and vibration due to shock formation. This problem is traditionally self-correcting, since the reduced efficiency when blade tips exceed Mach 1.0 tends to offset excess
power applied to the rotor, thus keeping the rotor speed in equilibrium. However, that
equilibrium speed is not optimal for efficient flight.

Such conventional methods and systems have generally been considered satisfactory for
their intended purpose. However, there is still a need in the art for improved rotor speed
management. The present disclosure provides a solution for this need.
SUMMARY OF THE INVENTION

A flight control system for a rotorcraft includes a controller configured to receive input indicative of ambient conditions, determine a threshold rotor blade tip speed based on the input, and to output rotor control commands to prevent rotor blade tips from exceeding the threshold speed. The threshold speed can be Mach 0.9 at the ambient conditions. The controller can be configured to output rotor control commands for control of coaxial main rotor assembly including an upper rotor assembly with a plurality of blades and a lower rotor assembly with a plurality of blades, wherein the rotor control commands prevent any blade tips of the upper and lower rotor assemblies from exceeding the threshold speed. The controller can be configured to receive input indicative of ambient conditions including ambient air temperature, prevailing wind speed, and/or prevailing wind direction.

An aircraft includes an airframe, a main rotor assembly operatively connected to the airframe, and a flight control system as described above. The flight control system is operatively connected to control the main rotor assembly. It is contemplated that the main rotor assembly can be a counter rotating coaxial main rotor assembly including an upper rotor assembly with a plurality of blades and a lower rotor assembly having a plurality of blades, wherein the flight control system is operatively connected to control both upper and lower rotor assemblies to prevent any blade tips of the upper and lower rotor assemblies from exceeding the threshold speed. The aircraft can include at least one of an ambient air temperature sensor, a rotor speed sensor, a prevailing wind speed sensor, and/or a prevailing wind direction sensor, operatively connected to provide input to the flight control system.

A method of controlling rotor speed on a rotorcraft includes receiving input from sensors indicative conditions ambient to a rotor, determining a threshold rotor blade tip speed based on
the input, and controlling rotational speed of the rotor to prevent any blade tips of the rotor from exceeding the threshold speed.

These and other features of the systems and methods of the subject disclosure will become more readily apparent to those skilled in the art from the following detailed description of the preferred embodiments taken in conjunction with the drawings.
BRIEF DESCRIPTION OF THE DRAWINGS

So that those skilled in the art to which the subject disclosure appertains will readily understand how to make and use the devices and methods of the subject disclosure without undue experimentation, preferred embodiments thereof will be described in detail herein below with reference to certain figures, wherein:

Fig. 1 is a side elevation view of an exemplary embodiment of a rotorcraft constructed in accordance with the present disclosure, showing the main rotor assembly with upper and lower coaxial counter rotating rotors, and schematically indicating the flight control system; and

Fig. 2 is a schematic view of the flight control system of Fig. 1.
DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made to the drawings wherein like reference numerals identify similar structural features or aspects of the subject disclosure. For purposes of explanation and illustration, and not limitation, a partial view of an exemplary embodiment of an aircraft in accordance with the disclosure is shown in Fig. 1 and is designated generally by reference character 100. Other embodiments of aircraft in accordance with the disclosure, or aspects thereof, are provided in Fig. 2, as will be described. The systems and methods described herein can be used to improve blade tip speed management in rotors such as in rotorcraft.

Aircraft 100 includes an airframe 102, a main rotor assembly 104 operatively connected to airframe 102, and a flight control system 106. Flight control system 106 is operatively connected to control main rotor assembly 104, translational thrust rotor assembly 116, tail fairing assembly 118, and one or more engines 120, as well as to receive inputs for flight control, as indicated by the large arrows in Fig. 1.

Main rotor assembly 104 is a counter rotating coaxial main rotor assembly including an upper rotor assembly 108 with a plurality of blades 110 and a lower rotor assembly 112 having a plurality of blades 110. Flight control system 106 is operatively connected to control both upper and lower rotor assemblies 108 and 112 to prevent any blade tips 114 of the upper and lower rotor assemblies 108 and 112 from exceeding a threshold speed.

Referring now to Fig. 2, aircraft 100 includes at least one of an ambient air temperature sensor, a rotor speed sensor, a prevailing wind speed sensor, and/or a prevailing wind direction sensor, operatively connected to provide input to the flight control system 106, as indicated by the sensor inputs 122 in Fig. 2. Flight control system 106 includes a controller 124, e.g., a flight control computer, configured to receive input indicative of ambient conditions, e.g., from sensor
Controller 124 also receives flight inputs 126, which can include any suitable inputs such as control input from a pilot, autopilot, guidance system, or the like. Controller 124 determines a threshold rotor blade tip speed based on the input. Controller 124 outputs rotor control commands to prevent rotor blade tips 114 from exceeding the threshold speed. The threshold speed can be Mach 0.9 at the ambient conditions, or any other suitable Mach number at ambient conditions for a given airfoil, airframe or application. For state of the art airfoils, maintaining tip speeds at or below Mach 0.9 mitigates or avoids the compressible flow regime effects, e.g., from exceeding the speed of sound, that might otherwise reduce blade efficiency and increase drag on the blades 110. For example, this can improve maximum cruise speed, range, and/or endurance compared to conventional systems. Those skilled in the art will readily appreciate that improvements in airfoil design can increase this threshold Mach number to a value closer to Mach 1.0, and that the threshold speed can be set at any suitable Mach number for a given application.

The threshold speed is based on the speed of sound at a given air temperature, so Mach 0.9 for example, corresponds to a different tip speed depending on ambient air temperature. The tip speed itself varies with rotational speed of the respective blade 110 as well as the aircraft speed and direction as well as any wind speed and direction. Using prevailing wind speed and direction from aircraft sensors accounts for both wind and aircraft movement, e.g., wind speed and direction, and aircraft speed and direction can all be accounted for as input from a true air speed sensor. Controller 124 uses this information to control the rotational speed of rotors 108 and 112 from ever exceeding a rotational speed that would cause tips 114 from exceeding the speed of sound, given air temperature, aircraft movement, and wind. A tip speed corresponding
to Mach 0.9 at ambient conditions suffices as a threshold for preventing tips 114 from exceeding
the speed of sound.

Controller 124 is configured, e.g., with machine readable instructions stored in memory
128 and/or processed in CPU 130, to receive input, determine the threshold speed, and output
5 rotor control commands for control of coaxial main rotor assembly 104 e.g., through engine
interface 134 and/or rotor interface 132, to control the rotational speed of rotors 108 and 112,
wherein the rotor control commands prevent any blade tips 114 of the upper and lower rotor
assemble 108 and 112 from exceeding the threshold speed as described above.

In this embodiment controller 124 is also connected to control translational thrust rotor
assembly 116 and tail fairing assembly 118, as indicated by translational thrust interface 136 and
tail fairing interface 138. Other embodiments can have other means of separately controlling the
translational thrust rotor, such as when said rotor is powered by a separate source/engine. The
two-way arrows in Fig. 2 indicate that in addition to issuing commands to the interfaces 132, 134,
136, and 138, controller 124 can also receive feedback from the respective interfaces and base
control commands on said feedback. The controller interface 140 interfaces the input/output of
flight control system 106 with the CPU 130 and memory 128 of controller 124.

A method of controlling rotor speed on a rotorcraft, e.g., aircraft 100, includes receiving
input from sensors, e.g., from sensor inputs 122, indicative conditions ambient to a rotor, e.g.,
rotors 108 and 112. The method also includes determining a threshold rotor blade tip speed
based on the input, and controlling rotational speed of the rotor, e.g., rotors 108 and 112, to
prevent any blade tips, e.g., tips 114, of the rotor from exceeding the threshold speed.

In addition to limiting maximum tip speed, it is also contemplated that the systems and
methods used herein can be used to maintain tip speed above a predetermined minimum speed.
It is also contemplated that the systems and methods described herein can be used to maintain blade tip speed between a predetermined maximum and a predetermined minimum speed.

The methods and systems of the present disclosure, as described above and shown in the drawings, provide for tip speed management with superior properties including improved efficiency and effectiveness. While the apparatus and methods of the subject disclosure have been shown and described with reference to preferred embodiments, those skilled in the art will readily appreciate that changes and/or modifications may be made thereto without departing from the scope of the subject disclosure.
What is claimed is:

1. A flight control system for a rotorcraft comprising:
   a controller configured to receive input indicative of ambient conditions, determine a threshold rotor blade tip speed based on the input, and to output rotor control commands to prevent rotor blade tips from exceeding the threshold speed.

2. The system recited in claim 1, wherein the threshold speed is Mach 0.9 at the ambient conditions.

3. The system recited in any of the preceding claims, wherein controller is configured to output rotor control commands for control of coaxial main rotor assembly including an upper rotor assembly with a plurality of blades and a lower rotor assembly with a plurality of blades, wherein the rotor control commands prevent any blade tips of the upper and lower rotor assemblies from exceeding the threshold speed.

4. The system as recited in any of the preceding claims, wherein the controller is configured to receive input indicative of ambient conditions including ambient air temperature.

5. The system as recited in any of the preceding claims, wherein the controller is configured to receive input indicative of ambient conditions including prevailing wind speed.

6. The system as recited in any of the preceding claims, wherein the controller is configured to receive input indicative of ambient conditions including prevailing wind direction.
7. An aircraft comprising:

an airframe;

a main rotor assembly operatively connected to the airframe; and

a flight control system as recited in any of the preceding claims, wherein the flight control system is operatively connected to control the main rotor assembly.

8. An aircraft as recited in claim 7, wherein the main rotor assembly is a counter rotating coaxial main rotor assembly including an upper rotor assembly with a plurality of blades and a lower rotor assembly having a plurality of blades, wherein the flight control system is operatively connected to control both upper and lower rotor assemblies to prevent any blade tips of the upper and lower rotor assemblies from exceeding the threshold speed.

9. An aircraft as recited in any of claims 7-8, further comprising at least one of an ambient air temperature sensor, a rotor speed sensor, a prevailing wind speed sensor, and/or a prevailing wind direction sensor, operatively connected to provide input to the flight control system.

10. A method of controlling rotor speed on a rotorcraft comprising:

receiving input from sensors indicative conditions ambient to a rotor;

determining a threshold rotor blade tip speed based on the input; and

controlling rotational speed of the rotor to prevent any blade tips of the rotor from exceeding the threshold speed.
11. The method as recited in claim 10, wherein the threshold speed is Mach 0.9 at ambient conditions.

12. The method as recited in any of claims 10-11, controlling rotation speed includes controlling both rotors of a coaxial dual rotor main rotor assembly to prevent any blade tips of the two rotors from exceeding the threshold speed.

13. The method as recited in any of claims 10-12, wherein receiving input includes receiving air temperature input from an air temperature sensor.

14. The method as recited in any of claims 10-13, wherein receiving input includes receiving prevailing wind speed input from a prevailing wind speed sensor.

15. The method as recited in any of claims 10-14, wherein receiving input includes receiving wind direction input from a wind direction sensor.
Fig. 2
**INTERNATIONAL SEARCH REPORT**

International application No.  
PCT/US 15/53163

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(8) - B64C 27/57 (2016.01)
CPC - B64C 27/57

According to International Patent Classification (IPC) & to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC (8): B64C 27/57 (2016.01)  
CPC: B64C 27/57

Documented searched other than minimum documentation to the extent that such documents are included in the fields searched

IPC (8): B64C 27/54 (2016.01); CPC: G05D 1/08, G05D 1/0608, G05D 1/0858, B64C 27/54, B64C 27/635; USPC: 244/17.13, 244/76R, 701/121, 701/7

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Google (Patents, Scholars); PatBase (All); search terms: flight control system rotorcraft rotor speed controller sensing air conditions sensors helicopter computer processor blade tip command output status air state air temperature environment ambient prevailing wind direction upper lower assembly

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>US 2005/0236518 A1 (SCOTT) 27 October 2005 (27.10.2005) entire document, especially Fig 1</td>
<td>3/(1), 3/(2), 12/(10), 12/(11)</td>
</tr>
<tr>
<td>Y</td>
<td>US 7,967,239 B2 (COTTON, et al.) 26 June 2011 (28.06.2011) entire document, especially Fig 1A; col 3</td>
<td>12/(10), 12/(11)</td>
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</table>

Further documents are listed in the continuation of Box C.

**Date of the actual completion of the international search**  
28 January 2016 (28.01.2016)

**Date of mailing of the international search report**  
12 FEB 2016

**Name and mailing address of the ISA/US**  
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents  
P.O. Box 1450, Alexandria, Virginia 22313-1450

**Authorized officer:** Lee W. Young  
PCT Helpdesk: 571-272-4300  
PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)
International search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [ ] Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:

2. [ ] Claims Nos.: because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically.

3. [x] Claims Nos.: 4-9, 13-15 because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- [ ] The additional search fees were accompanied by the applicant’s protest and, where applicable, the payment of a protest fee.
- [ ] The additional search fees were accompanied by the applicant’s protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- [ ] No protest accompanied the payment of additional search fees.