Lecture Notes for

AE 545- PRINCIPLES OF HELICOPTER AND VTOL FLIGHT

MODIFIED NAME: HELICOPTER DYNAMICS AND AEROMECHANICS

Instructor: Peretz P. Friedmann, FXB Professor
Department of Aerospace Engineering
University of Michigan

M, W, F 2:30-3:30 PM, 1032 FXB

OFFICE HOURS 3:30-4:30

Fall Semester 2003

COURSE OUTLINE – AE 545: FALL SEMESTER 2003

1. Description of various helicopter configurations and rotor-systems.

2. Introduction to rotary-wing aerodynamics.

3. Fundamentals of helicopter performance in hover and in forward flight.

4. Simple control concepts for helicopters, flapping dynamics and control moments.

5. Elementary VTOL stability and control.

   5.1 Force and moment derivatives.

   5.2 Automatic stabilization of helicopters.

6. Rotary-wing aeroelasticity.

   6.1 Classical flap-pitch flutter of rotor-blades.

   6.2 Flap-lag stability in hover

   6.3 Coupled flap-lag-torsional stability in hover and forward flight

7. Coupled rotor/fuselage aeromechanical stability problems.

   7.1 Ground resonance.

   7.2 Air resonance in hover and forward flight.

   7.3 Control of the air-resonance problem.

8. The helicopter vibration problem in forward flight.

THE HELICOPTER? Here's what Wilbur Wright once said about it...

"Like all novices we began with the helicopter (in childhood) but soon saw it had no future and dropped it. The helicopter does, with great labor, only what the balloon does without labor, and is no more fitted than the balloon for rapid horizontal flight. If its engine stops it must fall with deathly violence, for it can neither float like the balloon nor glide like the airplane. The helicopter is much easier to design than an airplane, but it is worthless when done. "...15 January 1909

AE 545 – Principles of Helicopter and V/TOL Flight (Helicopter Dynamics and Aeromechanics)

List of Books on Helicopters

1. Baskin, V. E., Vildgrube, L. S., Yozbdayer, Y. S. and Maykapar, G. I., "Theory of the Lifting Airscrew," NASA TTF-823, 1976.   _러시아, National 언어??_

2. Bielawa, R. L., Rotary-Wing Aeroelasticity and Structural Dynamics, AIAA Education Series, AIAA, 1992.

3. Bramwell, A. R. S, Done, G. and Balmford, D, <u>Bramwell's Helicopter Dynamics, Second Edition,</u> AIAA, 2001.

4. Gessow, A. and Myers, G. C., <u>Aerodynamics of the Helicopter,</u> Frederick Ungar Pub. Co., New York, Third Printing 1952.

5. Johnson, W., <u>Helicopter Theory,</u> Dover Publications, 1994.   _Very Comprehensive Useful for research_

6. Mil, M. et al, "Helicopters – Calculation and Design: Vol. I Aerodynamics," NASA TTF- 494, 1967.   _러시아_

7. Mil, M. et al, "Helicopters – Calculation and Design: Vol. II Vibrations and Dynamic Stability," NASA TTF- 519, 1968.

8. Prouty, R. W., <u>Helicopter Performance Stability and Control,</u> PWS Engineering Boston, 1986.   _A lot of mistake_

9. Seddon, J. and Newman, S., <u>Basic Helicopter Aerodynamics, Revised,</u> AIAA Education Series, 2001.

10. Stepniewski, W. Z. and Keys, C. N., <u>Rotary-Wing Aerodynamics,</u> Dover Publications, 1984.

**11. Leishman, J. G., <u>Principles of Helicopter Aerodynamics,</u> Cambridge University Press, 2000, second printing soft cover edition available.

12. Padfield, G. D., <u>Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modeling,</u> AIAA Education Series, 1996.

13. A lot of useful material can be also found in the Journal of the American Helicopter Society, which is a quarterly journal.

Administrative Details for AE 545 – Principles of Helicopter and V/TOL Flight (Helicopter Dynamics and Aeromechanics)

- Approximately 5-6 Homework problem sets will be given--- 40% of grade
- Final Exam, open book, open notes---45% of grade
- Mini-term project, aimed at testing your ability to read and critique a paper—10% of grade
- Discretionary---5%
- Prerequisites:
    - AE315-Aircraft and Space craft Structures
    - AE525-Aerodynamics
- Course Tools Website: http//coursetools.ummu.umich.edu/2003/fall/aerosp/545/001.nsf

Details on the Helicopter Industry

- The aerospace industry excluding space is approximately a $130 billion/year industry
- The rotary wing industry is approximately $7-9 billion/year or ~6%
- Helicopter companies in the US: Bell, Boeing, Enstrom, Kaman, Robinson, Sikorsky
- Countries that have a helicopter industry: England, France, Germany, India, Italy, Japan, Russia
- AHS-International is an organization exclusively devoted to rotorcraft

Helicopters: An Overview

A helicopter might be defined (W. Johnson, p. 3) as an aircraft that uses rotating wings to provide lift, propulsion, and control. The word was introduced in France (as l'hélicoptère), based on the Greek *helix* (spiral) and *pteron* (wing).

The lift of a helicopter or an airplane can be interpreted in terms of a mass flow of air, per unit time, that is given an increase in downward velocity. The lift thus is equal to the time rate of change of vertical momentum of the air that is influenced by the vehicle. The pressure difference between upper and lower wing (or blade) surfaces can be simulated by introduction of a distribution of bound vorticity, which implies also trailing vorticity. While for an airplane the trailing vortices extend rearward with only a small downward deflection, for a hovering helicopter these vortices spiral directly downward below the rotor. The trailing vortices induce a downward velocity at the wing or the rotor blades, requiring a correction to the angle of attack used in calculating the lift at a wing or blade section.

To increase lift, the pilot increases the blade pitch angles by a rearward displacement of the collective pitch lever. Traditionally the change in pitch angle is allowed by a pitch hinge near the root of each blade. For transition to forward flight, the helicopter must be tilted slightly forward. This is accomplished by a forward displacement of the cyclic pitch stick, which leads to a cyclic variation of the blade pitch angles and a small forward tilt of the rotor disk. The thrust vector is likewise tilted, to give a pitch moment about the helicopter center of gravity and therefore a pitch acceleration of the helicopter fuselage.

A single-rotor helicopter has its advancing blade on the right and its retreating blade on the left; exceptions are helicopters built in France and in Russia. The rotor can be thought of as a gyroscope, so that a torque resulting from decreased lift on the advancing blade and increased lift on the retreating blade is (by a right-hand rule) regarded as directed forward, and thus requires a change in the angular momentum vector that is directed forward, accomplished by a forward tilt of the rotor disk and therefore of the rotor angular momentum vector. Another view is that the rotor is a mechanical system forced at its natural frequency, so that the response lags the force by a phase angle of $\pi/2$.

In forward flight the advancing blade sees an increased relative air velocity, while the retreating blade sees a decreased relative air velocity. The dynamic pressure and lift are thus increased on the advancing blade and decreased on the retreating blade. This would lead to a rolling moment unless a correction were made. Moreover, the time-dependent lift force leads to a strong time-dependent structural bending moment at the blade root. Traditionally, these

issues have been addressed by the introduction of flapping hinges near the blade roots, so the blades are free to undergo a small amount of flapping motion (limited by centrifugal forces). In addition, Coriolis forces introduce in-plane bending moments that have traditionally been relieved by lag hinges (with damping to limit the lead-lag motion). In current helicopter designs one or more of the hinges is replaced by a bearing or a flexible structural member between the main part of the rotor blade and the rotor shaft. The idea of equivalent hinges displaced somewhat further outward from the rotor axis allows analysis of blade motion in a manner similar to that for articulated rotors.

The torque applied to the rotor implies an equal and opposite torque applied to the fuselage, which must be balanced in some way. The most common configuration uses a vertical tail rotor, or anti-torque rotor. Changing the blade pitch angles on the tail rotor allows yaw control. Pitch and roll control are achieved through use of cyclic pitch of the main rotor blades, which allow tilting of the main rotor. The alternative would be the use of contrarotating rotors, with three main possibilities: tandem, coaxial, or side-by-side rotors; examples either exist or have been tried for each type. Yaw, pitch, and roll control are accomplished through different combinations of collective and cyclic pitch of the two rotors.

A number of helicopter models were designed in the late eighteenth and in the nineteenth century. But development of the piloted helicopter, as of the airplane, required an engine with high power-to-weight ratio, which became available with the advent of the reciprocating internal combustion engine. The first helicopter "flights" might be said to have taken place in France in 1907, just four years after the first Wright brothers' flight. Breguet's 4-rotor helicopter reached a height of about 1 meter for about one minute, but was held by four men; Cornu's tandem twin-rotor helicopter reached 0.3 meter for 20 seconds.

In the 1920's many of the significant developments were associated with the autogiro. The thrust for an autogiro is provided by a propeller, while the rotor provides only lift. The rotor is tilted slightly rearward and is driven by an upward airflow, rather than by the engine. While the use flapping hinges had been proposed as early as 1904, the idea was first applied to an autogiro by de la Cierva (Spain, 1923). The autogiro is capable of very low forward speeds but of course can not hover.

Many different helicopter designs were introduced, in Europe and the United States, during the 1920's and 1930's. The use of cyclic pitch for control of a helicopter was first demonstrated by Pescara in 1924. The first helicopter to carry out repeated sustained flight was a side-by-side twin-rotor helicopter designed by Focke in Germany and flown in 1937; cyclic pitch provided directional and longitudinal control, and differential collective pitch

allowed roll control.   For the single-rotor helicopter, the idea of a tail rotor to balance main-rotor torque was known in 1912 and used in flight in the mid-1920's.

Igor Sikorsky initially experimented with helicopters in Russia in 1907-1910, but then turned to development of airplanes.   Returning to helicopters in the United States, he completed the design of a successful single-rotor helicopter, with anti-torque tail rotor, and utilizing collective and cyclic pitch, in 1941.   This aircraft is usually considered to be the first practical helicopter; later versions were put into production in the following few years, during World War II.   In subsequent years other designs were also developed, with various configurations and a wide variety of sizes, by a number of companies in the U. S., as well as in Russia, England, France, Germany, and other countries.   An important development was the replacement of the piston engine with the turboshaft engine, starting in the early 1950's and now standard in all helicopters except the very smallest.

It was Sikorsky who once stated that the helicopter is the only human invention that has saved more lives than it has cost.   It was also once said that seven lives had been saved for every helicopter that had been built.   These statements reflect some of the many civilian uses of the helicopter, that perhaps are not sufficiently well known in comparison with the obvious military applications.   Civil applications might be conveniently summarized under six general headings:

transport: scheduled air service, charters, executive transport

offshore oil support: Gulf of Mexico, North Sea, and elsewhere

agriculture: crop spraying, dusting, seeding

heavy lift: construction (e. g., power lines), logging

public service: police, fire-fighting, ambulance, rescue

other aerial work: press, TV, aerial photography; surveying, pipeline or power-line
    inspection; etc.
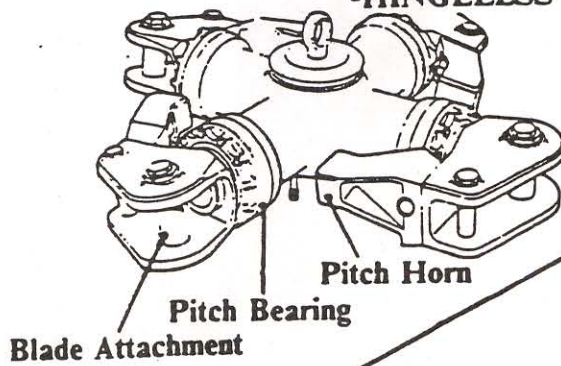
HELICOPTER ROTOR CONFIGURATIONS

-ARTICULATED ROTOR-

Lag Hinge

Blade Attachment

MBB BO105

Lag Damper

Pitch Horn

Flap Hinge

Blade Attachment

Pitch Bearing

-HINGELESS ROTORS-

Lag Damper

Pushrod

Pitch Horn

Pitch Bearing

Blade Attachment

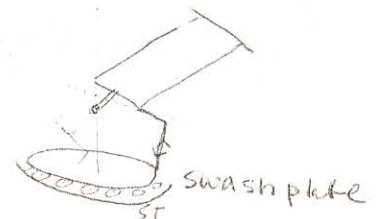Absolutely No hinge

-BEARINGLESS ROTOR-

Flexbeam

Blade Attachment

Pitch Horn
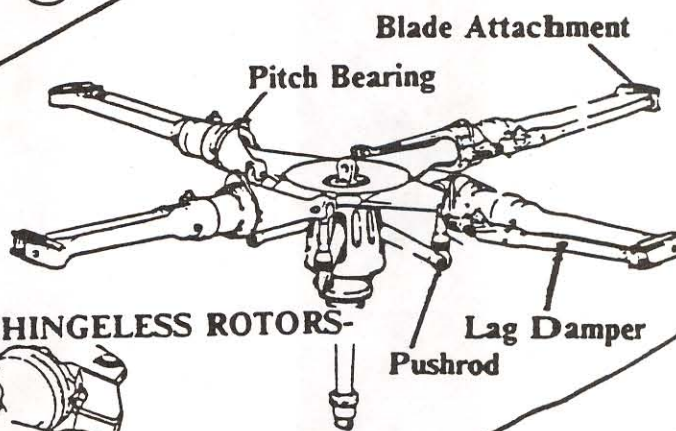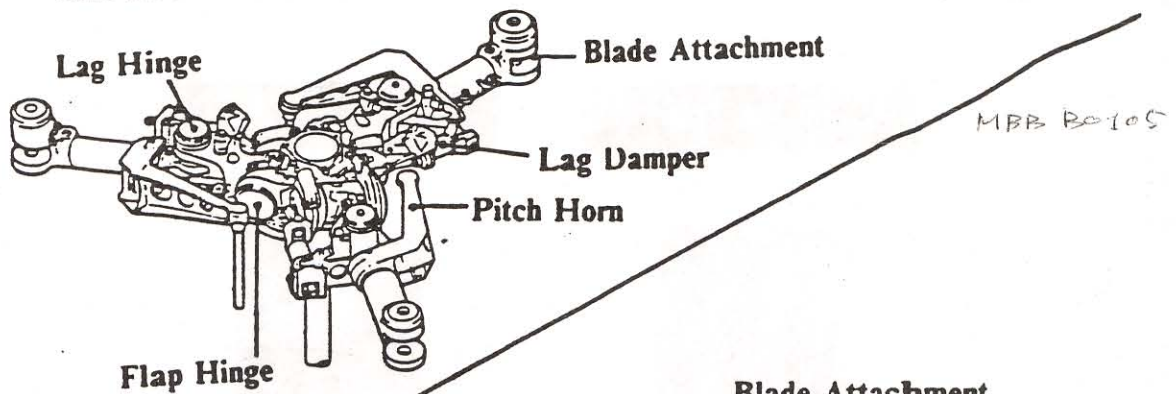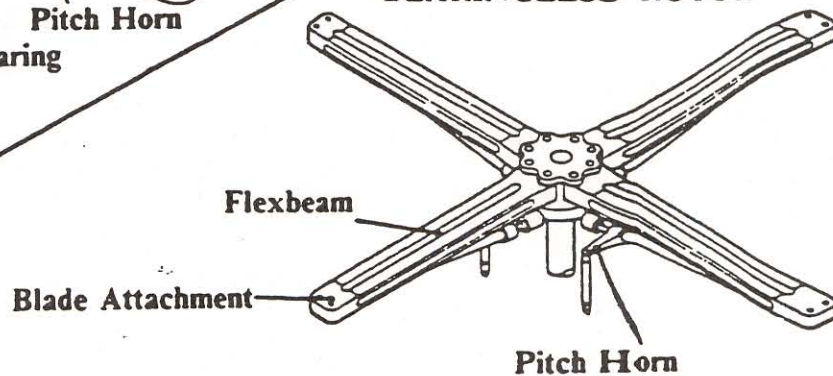
Figure 1: Articulated, hingeless, and bearingless rotors.
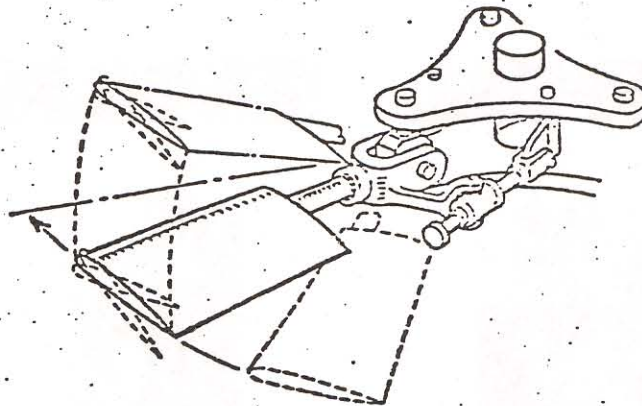
swashplate

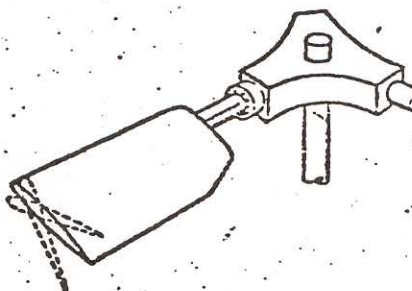Fig. 4a. An Articulated Rotor
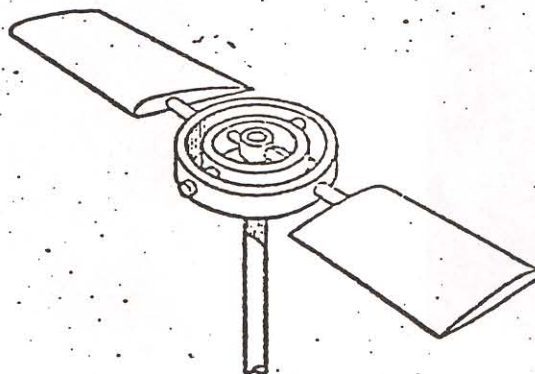
Fig. 4b. A Semi-rigid Rotor

Fig. 4c. A Rigid Rotor

3—(A.501)
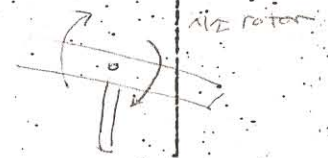
TILTS AND ROTATES

TILTS ONLY
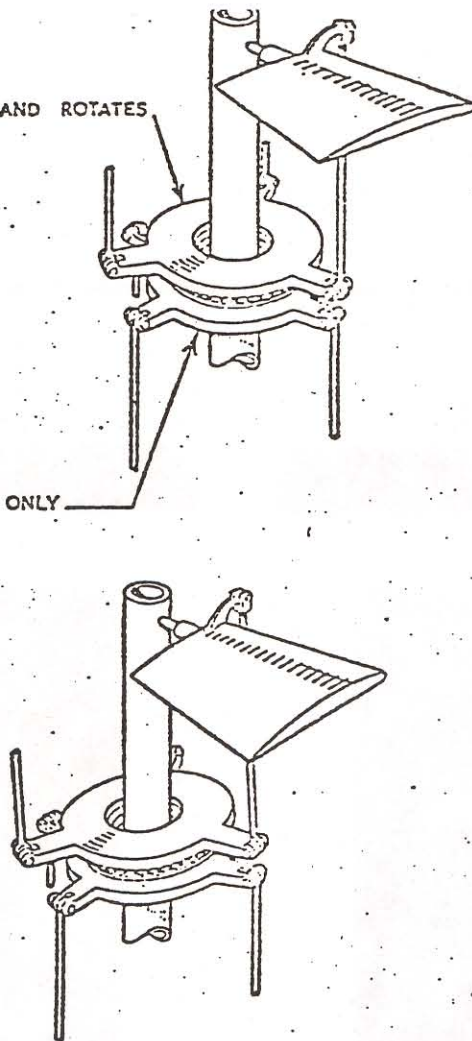
Fig. 5a. The Swash-plate System for Changing Cyclic Pitch
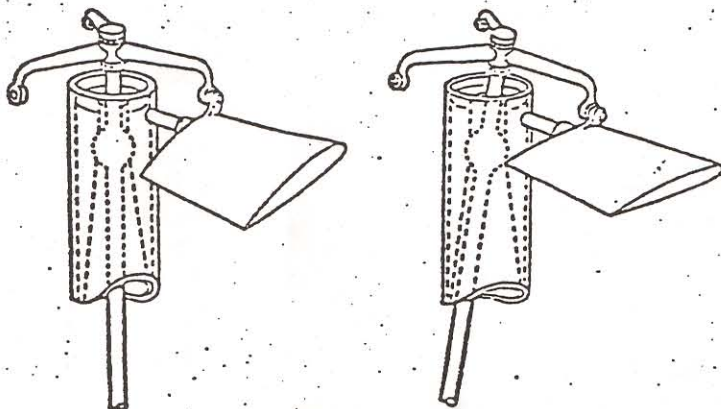
Fig. 5b The Spider System for Changing Cyclic Pitch
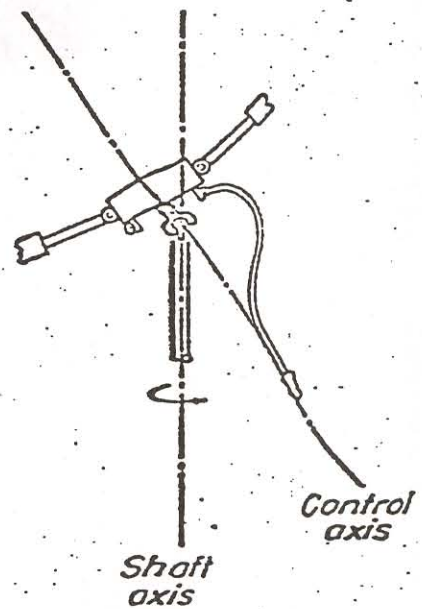
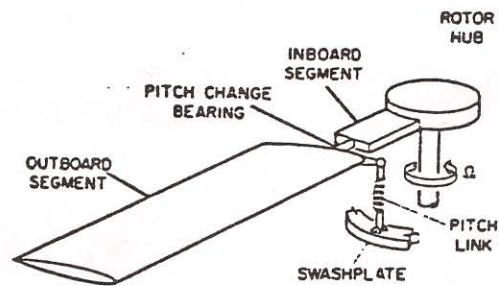Fig. 5c Control by tilting hub with respect to shaft.

Control axis

Shaft axis

Fig. 1 Primary elements of general
hingeless rotor configuration.
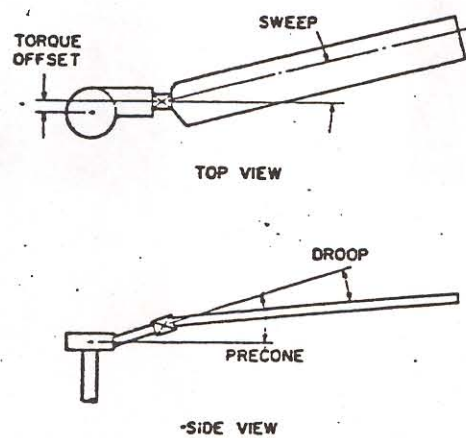
Fig. 2 Configuration parameters of
hingeless rotor blades.

BEAM FLEXURE

LEADING
EDGE BEAM

TRAILING
EDGE BEAM

CLEVIS

MODIFIED
BO-105 BLADE

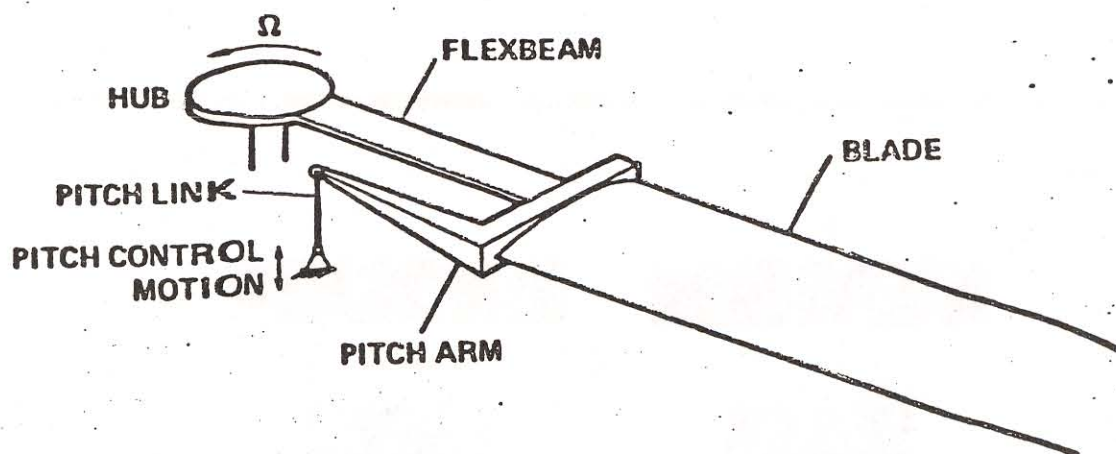PITCH LINK
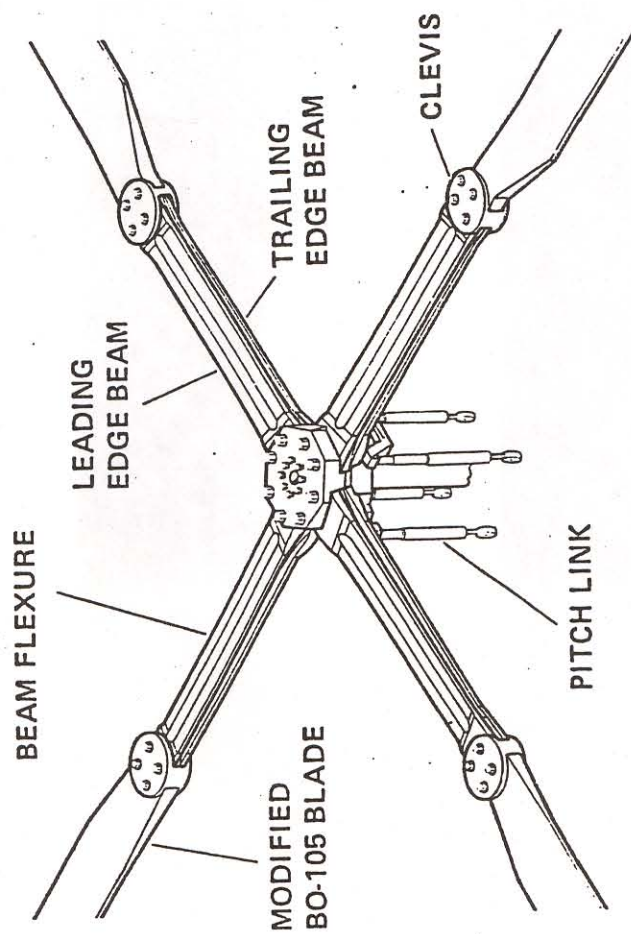
TYPICAL BEARINGLESS ROTOR

Figure 5.– Cantilever pitch arm, Case III.
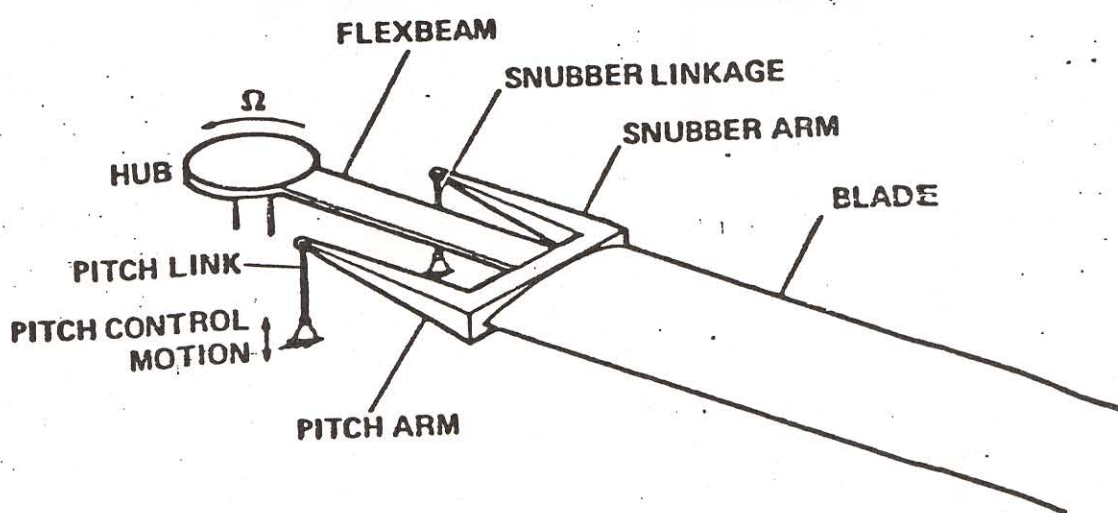
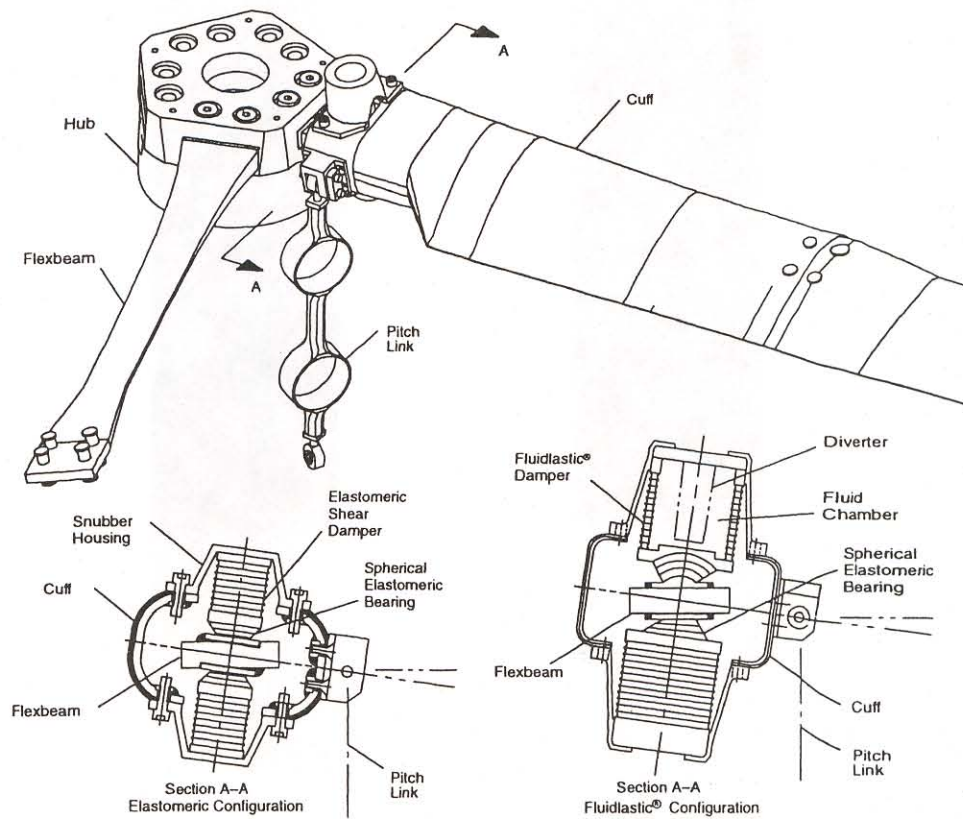Figure 6.– Cantilever pitch arm with snubber, Case IV.

FLEXBEAM TYPE OF
BEARINGLESS ROTOR

TORSION

LAG

FLAP

YAW

Ω

TAIL ROTOR

4 - BLADED
MAIN ROTOR

ROLL

PITCH
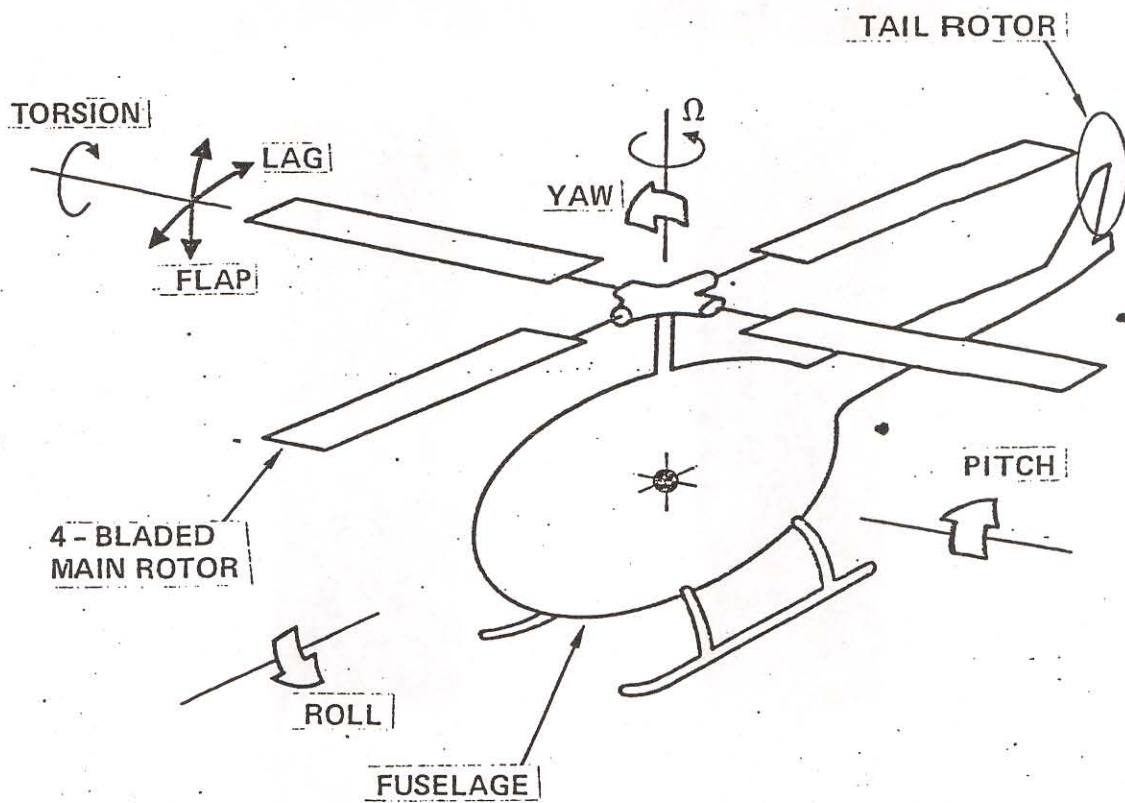
FUSELAGE

* COUPLED ROTOR/FUSELAGE SYSTEM

13a

Comanche Bearingless Main Rotor