6. Autorotation in Vertical Descent

2020

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Overview

- I. Energy balance in autorotation
- II. Forces on the blade element in autorotation
- III. Autorotation diagram
- IV. Most efficient AoA for autorotation
- V. Statement of the performance problem
- VI. Flow states of the rotor
- VII. Performance calculation in vertical descent
- VIII. Rotor drag coefficient in vertical descent

Introduction

STRAPPED INTO A FALLING HELICOPTER - Smarter Every Day 154 <https://www.youtube.com/watch?v=BTqu9iMiPIU&t=329s>

Introduction

- What is Autorotation?
  - When no power is supplied through the rotor shaft

    ➡ Lifting rotor is driven in rotation by air forces
  - Power required to produce induced and profile-drag power must be supplied from some external sources
    - Autogyro : propeller (at the front of fuselage)
    - Helicopter in power-off condition : force of gravity
- Question: what will be its minimum R/D in steady autorotation?
  - Capable of producing high resistances
  - Capable of supporting the helicopter in descent at low R/D

  ➡ A rotor in vertical autorotation is as effective in producing resistance as a parachute of the same diameter

* R/D: rate of descent

I. Energy balance in autorotation

❖ Power-off flight

25~50% of the total rotor losses

$$\boldsymbol{WV_v = Wv + profile\ drag\ power}$$

* W : Weight of the helicopter

* V_v : Rate of descent

* v : Mean effective induced velocity

- R/D ~ profile power

→ blades should be as smooth as possible, good airfoil section

→ little profile drag → low R/D

II. Forces on the blade element in autorotation

- Lift vector tends to accelerate the blade element in the direction of rotation
- Optimum autorotative performance @ moderate positive pitch angles

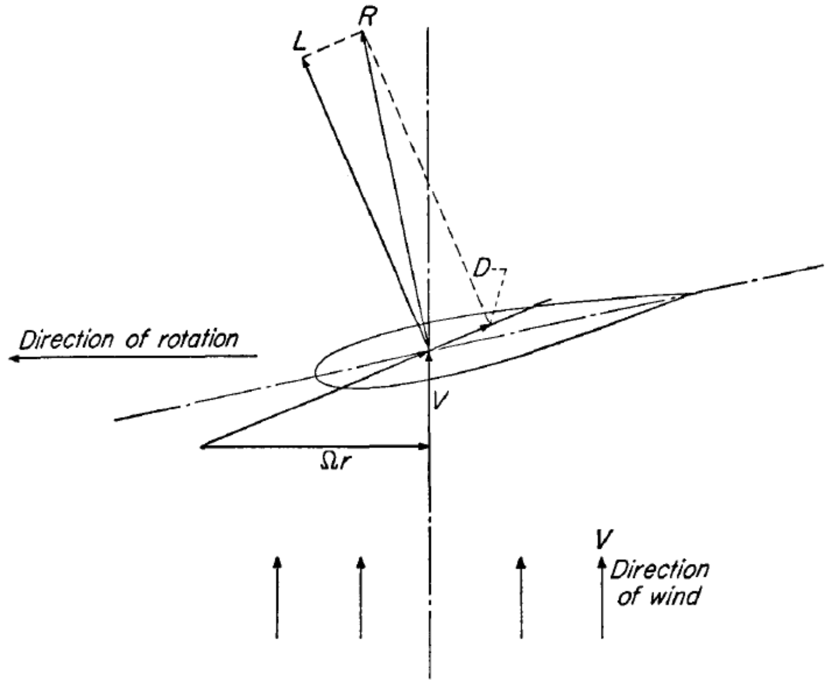

Fig. 6–1 Forces acting on a windmilling blade element.

Windmilling	Autorotation
blade settings that produce max. torque / (-) angles but also resistance	Blade settings that produce max. axial resistance @ zero torque / (+)angles

II. Forces on the blade element in autorotation

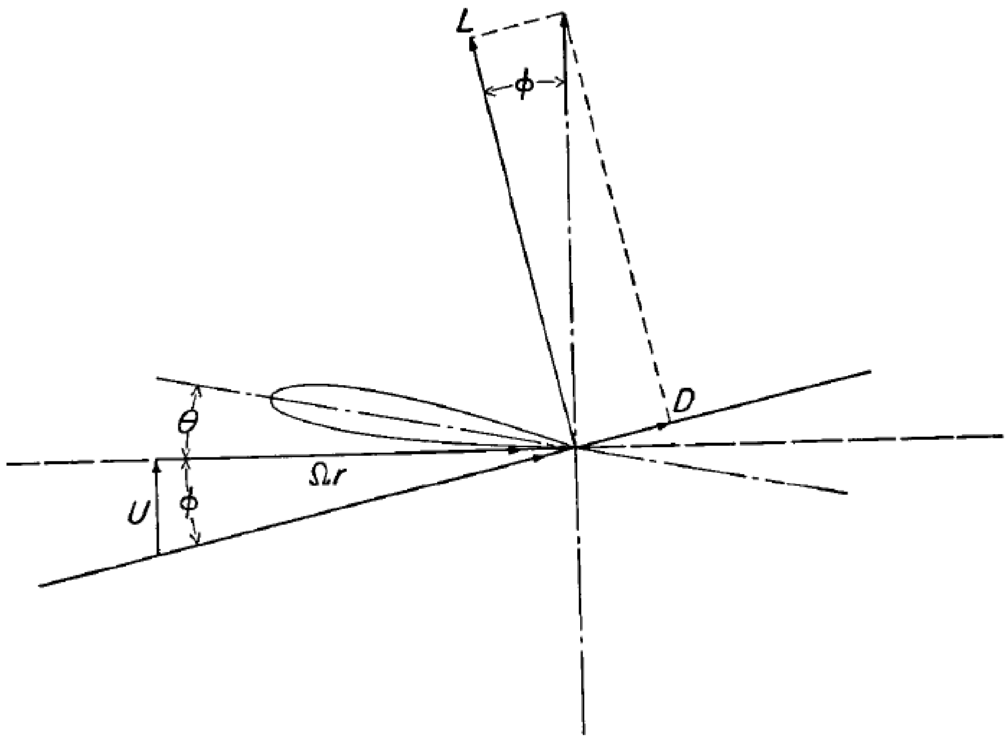

Fig. 6–2 Blade element in autorotation.

- Normal autorotation : no accelerating or decelerating in-plane forces

1) Inflow angle $\phi = \frac{u}{\Omega r} = \frac{C_{d_0}}{C_l}$ (1)

2) Autorotative equilibrium $C_{d_0} = C_l \phi$ (2)

3) Blade AoA $\alpha_r = \theta + \phi$ (3)

III. Autorotation diagram

❖ Airfoil section characteristics ($\frac{C_{d_0}}{C_l}$) vs. blade section AoA α_r

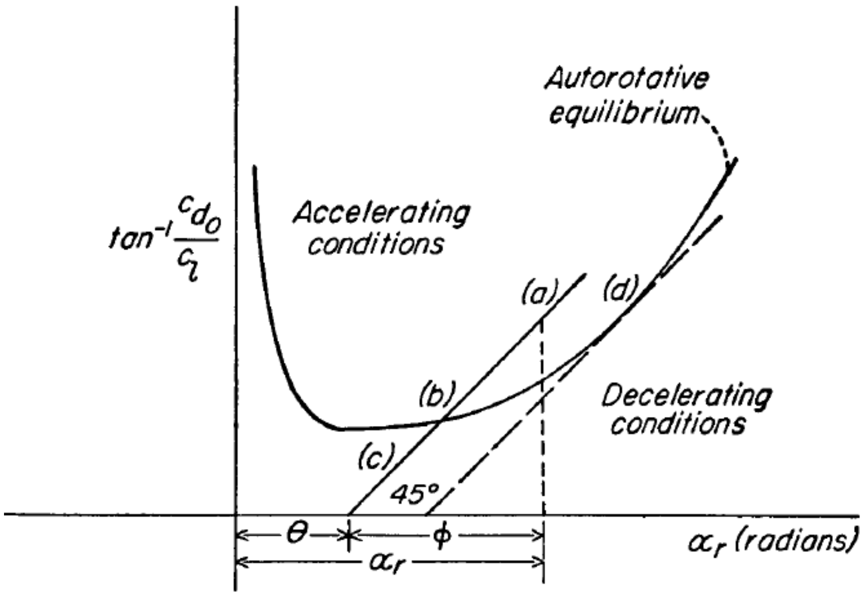

Fig. 6–3 Autorotation diagram for investigating equilibrium conditions at a blade element.

(a) $\phi > \frac{C_{d_0}}{C_l}$, resultant force R

accelerates blade element

→ increase $\Omega r \rightarrow \phi$ decreases

→ accelerate until (b)

(a), (b), autorotative equilibrium

since $\phi = \frac{C_{d_0}}{C_l}$ → "autorotative

equilibrium curve"

III. Autorotation diagram

- **Above** the curve, (a) → **accelerating** condition, resultant vector falls **ahead**
- **On** the curve, (b) → **autorotative** equilibrium, resultant vector falls **along** the rotor axis
- **Below** the curve, (c) → **decelerating** equilibrium, resultant vector falls **behind**
- (d) → highest possible value of the pitch angle

❖ Variation of rotation speed vs. blade pitch

- Φ varies inversely with Ωr
- Highest rotation speed corresponds to the lowest Φ

→ pitch for max. rotor speed is therefore the pitch defined by the intersection of a 45° line through the min. of the $\frac{C_{d_0}}{C_l}$ curve

→ Highest possible pitch for autorotation (d)

IV. Most efficient AoA for autorotation

- Aim in the design of autorotating rotor
  - Obtain minimum R/D @ a given helicopter GW and horizontal velocity
- Optimum blade AoA ~ angle for minimum profile-drag power

$$d\,(profile\ drag\ power) = \frac{1}{2} C_{d_0} \rho (\Omega r)^2 c d_r (\Omega r) \quad (4)$$

- For a given element, *profile-drag power* ~ $C_{d_0} (\Omega r)^3$

$$dT = C_l \frac{1}{2} \rho (\Omega r)^2 c d_r \quad (5)$$

- for a given thrust, $(\Omega r) \sim \frac{1}{\sqrt{C_l}}$

➔ Profile power $\boldsymbol{\sim C_{d_0} (\Omega r)^3 \sim \frac{C_{d_0}}{{C_l}^{3/2}}}$ (6)

- For minimum rotor sinking speed, $\frac{C_{d_0}}{{C_l}^{3/2}}$ should be as low as possible
- For good efficiency, operating AoA in reasonably high range below stall angle

IV. Most efficient AoA for autorotation

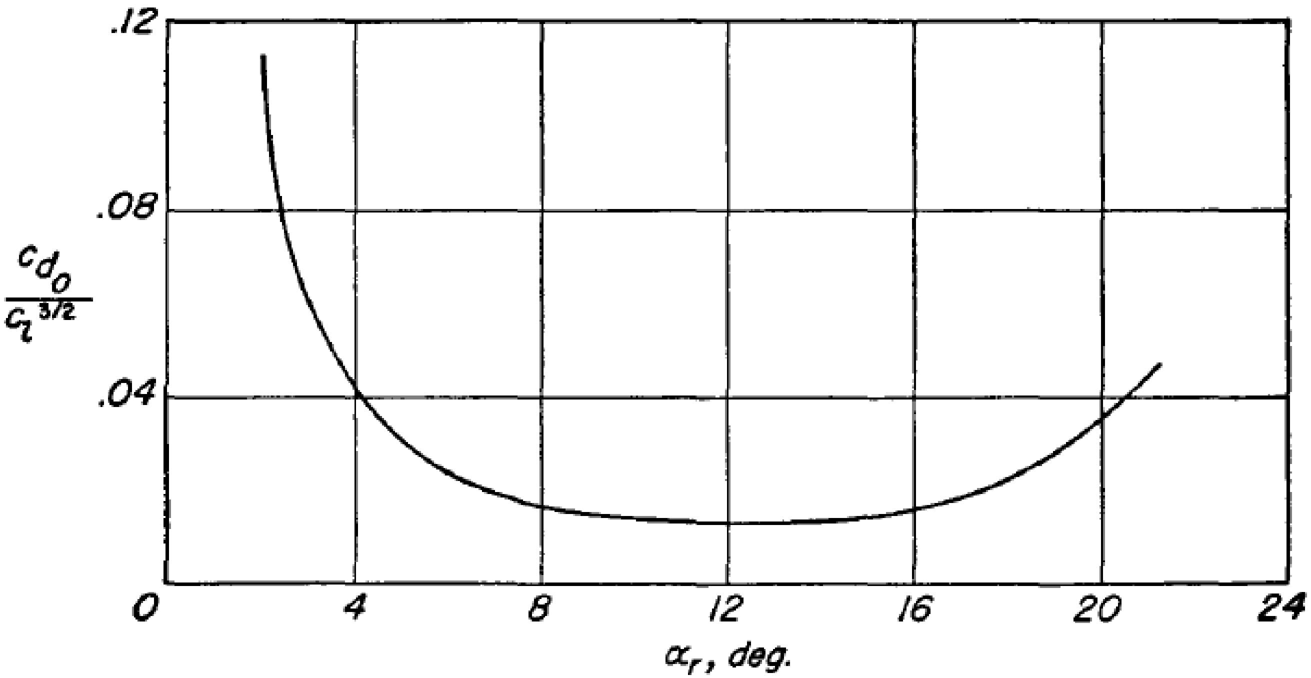

Fig. 6–4 Section characteristics of a practical-construction NACA 23012 airfoil.

❖ For good efficiency, operating AoA could be anywhere in reasonably high range below stall angle

V. Statement of the performance problem

- Relationships between the power required to hover and the major variables – *thrust, rotation speed, pitch, solidity, profile drag*
- Problem in vertical autorotative descent : variables vs. R/D
  1. Blade element thrust equation
  2. Blade element torque equation
  3. Momentum equation
- Momentum equation assumes that definite slipstream exists

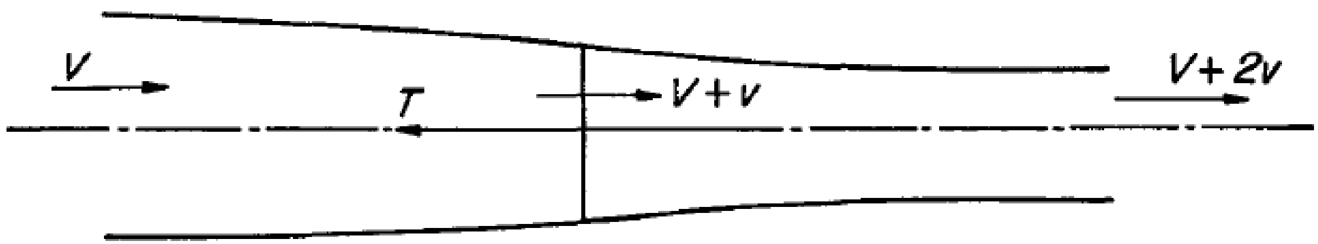

Fig. 6–5 Slipstream of an airscrew as derived from momentum considerations.

- Must be intermediate states where no definite slipstream exists

VI. Flow states of the rotor

❖ Flow states of the rotor in vertical flight

1. Normal working state…

- air approaches the rotor in the same direction as the induced velocity. Flow is downward through the rotor disk. Velocity at the disk is equal or greater than the induced velocity

2. Vortex ring state…

- definite slipstream does not exist any more. Flow at the disk is still downward, but far above the rotor, upward flow. Large recirculating flow

3. Windmill-brake state…

- large R/D definite slipstream, up through the rotor disk. Considerable recirculation and turbulence @ low R/D

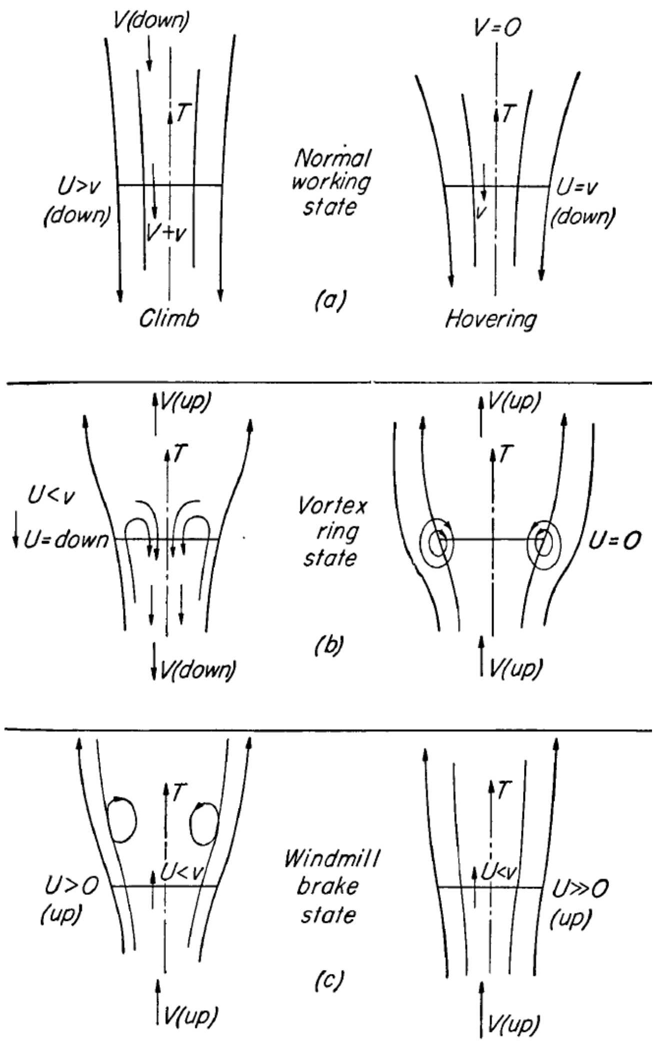

Fig. 6–6 Flow states of an airscrew.

VII. Performance calculation in vertical descent

❖ Application of momentum equation to vortex ring state…

- limited, but interesting to estimate "mean" induced velocity

❖ Normal working state

(+) when directed downward

$$T = \pi R^2 \rho (v + V_v) 2v \quad (7)$$

❖ Windmill-brake state

$$T = 2\pi R^2 \rho (-V_v - v) v \quad (8)$$

❖ Non-dimensional velocities

- Non-dimensional induced velocity $\bar{v} = \dfrac{v}{\sqrt{\frac{T}{2\rho\pi R^2}}}$ (9)
- Non-dimensional R/C $\bar{V}_v = \dfrac{Vv}{\sqrt{\frac{T}{2\rho\pi R^2}}}$ (10)

(7) → normal working state : $1 = \bar{v}(\bar{v} + \bar{V}_v)$, $\bar{V}_v = \frac{1}{\bar{v}} - \bar{v}$ (11)

Windmill-brake state : $1 = -\bar{v}(\bar{v} + \bar{V}_v)$, $\bar{V}_v = -\frac{1}{\bar{v}} - \bar{v}$ (12)

VII. Performance calculation in vertical descent

- relationship plot but limits occur
  - Normal working state… $\bar{v} > 1$
  - Windmill-brake state… $\bar{v} > -\frac{1}{2}\bar{V}_v$, $\bar{v} > 1$

    → Dashed lines in Fig. 6-7
  - Mean effective induced velocity in the vortex-ring state in partial-power and power-off descent

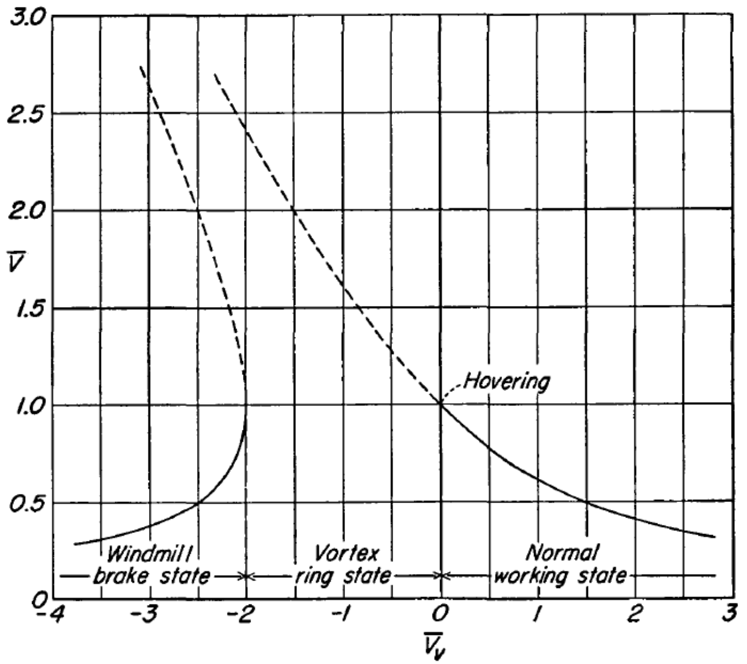

Fig. 6-7 Theoretical induced-velocity parameter. (Dashed lines indicate region wherein momentum concepts do not apply.)

- Power at the shaft

$$Shaft\ power = TV_v + Tv + \frac{\delta\rho}{8}(\Omega R)^3\sigma\pi R^2 \quad (13)$$

* δ : mean blade section drag coefficient @ $Cl_{mean} = \frac{6C_T}{\sigma}$

Eq. (13) can be rewritten in non-dimensional : $C_a = \frac{\sigma\delta}{8} + (\bar{v} + \bar{V}_v)\frac{{C_T}^{3/2}}{\sqrt{2}}$ (14)

→ Little reliable data to predict the mean effective induced velocity

VII. Performance calculation in vertical descent

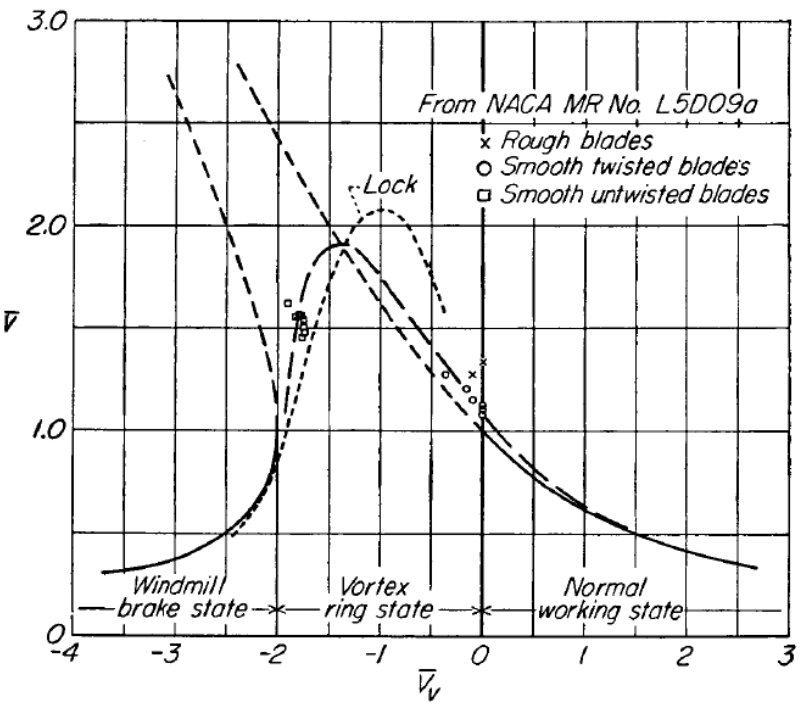

Fig. 6-8 Empirical curves of $\bar{v}$ *versus* $\bar{V}_v$ in vortex-ring state.

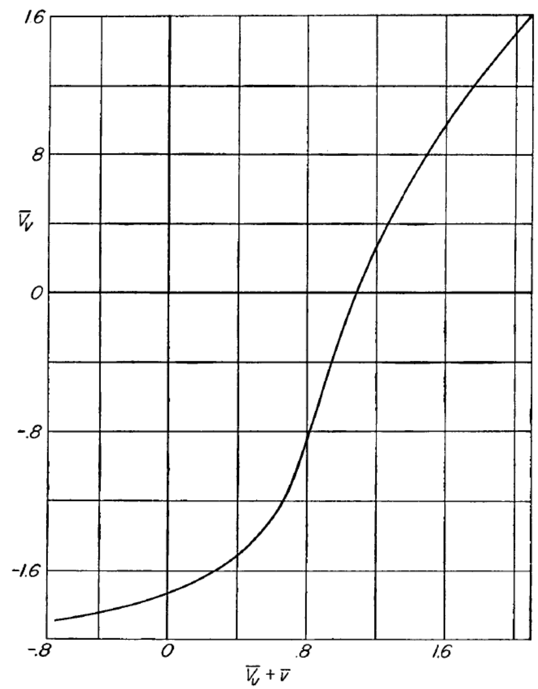

Fig. 6-9 Empirical curve for calculating vertical-descent velocities.

- **Fig. 6-8** : NACA test data → good agreement

  → replot in terms of $\bar{v} + \bar{V}_v$ against $\bar{V}_v$ → **Fig. 6-9** potential-power descent performance

- Mean drag coefficient … constant profile-drag coefficient is quite satisfactory

  but may underestimate the profile losses

VIII. Rotor drag coefficient in vertical descent

❖ Vertical autorotation…

- consider the rotor simply as a disk providing resistance

→ overall resistance expressed in terms of rotor drag coefficient…

$$C_{D_R} = \frac{thrust}{\frac{1}{2}\rho {V_v}^2 \pi R^2} \qquad (15)$$

1) Circular plate… 1.28
2) Parachute, anemometer cup shape… 1.4
3) If as in Fig. 6-10

$\rightarrow T = \rho \pi R^2 V^2,\ \ C_{D_R} = 2.0\ (limiting\ value)$

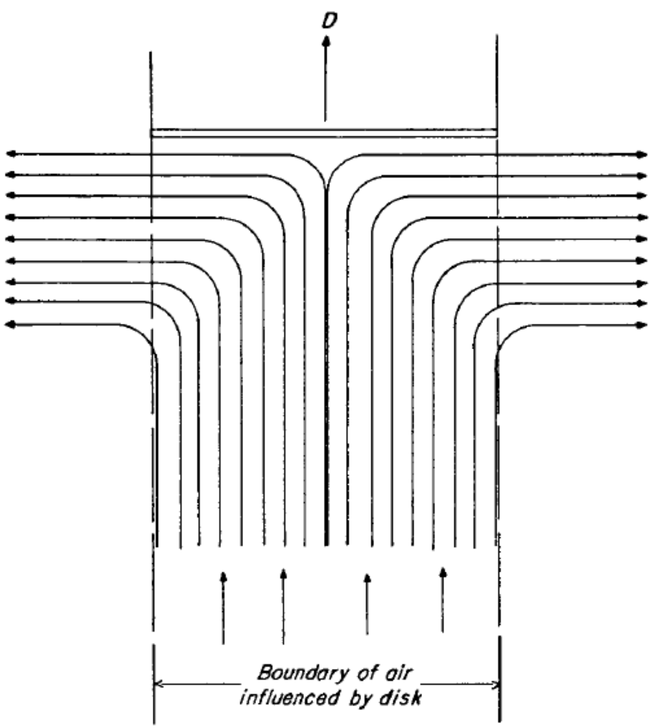

Fig. 6–10 Flow picture for calculating drag of disk by Newton's law.

VIII. Rotor drag coefficient in vertical descent

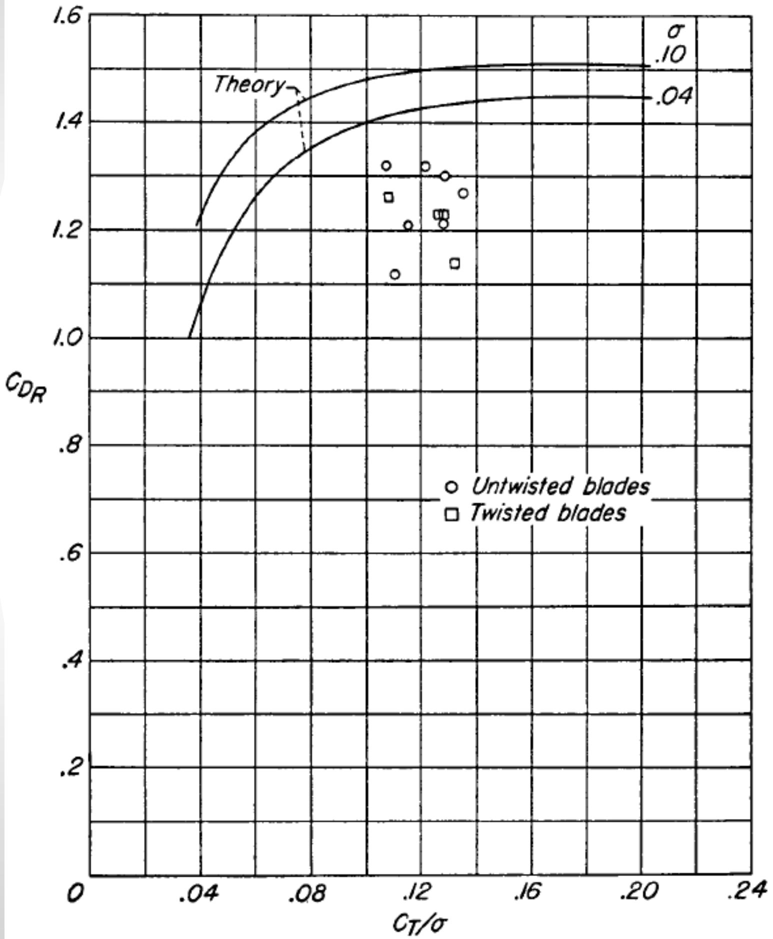

Fig. 6-11 Experimental vertical-autorotative-descent data and a comparison with theory.

❖ Experimental results

- 1.2 for rotors at normal pitch angles
- Plotted for 2 different σ (solidity)
- Theory overestimates C_{D_R} by 15%
  → R/D can be underestimated

❖ Effect of pitch

- Ω can be kept in the range of normal operating values
- R/D does not vary with pitch

❖ Effect of twist

- Twist, untwist -> same R/D