# Rotor 16

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## About

Rotor 16 is part of a research program to study the effect of weight flow per unit annulus area on the performance of axial-flow fan stages. A series of three stage: rotor 11, 16 and 17 were designed with a weight flow per unit annulus area of 198, 178, and 208 kilograms per second per square meter. All three stages were designed to produce a pressure ratio of 1.57, and all had the same meridional flow path geometry.

- Original technical report [(cite:moore1973design>Moore *et al* «Performance of transonic fan stage with weight flow per unit annulus area of 178 kilograms per sercond per square meter (36.5 (lb/sec)/ft²) » 1973. pdf)]:

```
@TechReport{moore1973design,
  author           = {Moore, R. D. and Urasek, Donald C. and Kovlch,
George},
  date             = {1973},
  institution      = {NASA Lewis Research Center Cleveland, OH, United
States},
  title            = {Performance of transonic fan stage with weight flow
per unit annulus area of 178 kilograms per sercond per square meter (36.5
(lb/sec)/ft²)},
  number           = {NASA-TM X-2904},
  url              = {https://ntrs.nasa.gov/citations/19740001906},
}
```

- Picture :

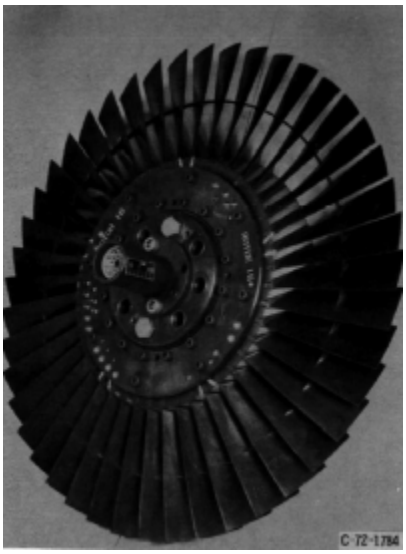


Fig1. https://ntrs.nasa.gov/citations/19740001906 p.64

**Useful documents**

- downloadable models (Git project)
  - NASA technical report (.pdf)
  - geometrical parameters file (.csv), usable as input of OpenMCAD[(cite:Kojtych_2022_gene_aubes>Kojtych S., Batailly A. «OpenMCAD, an open blade generator: from Multiple-Circular-Arc profiles to Computer-Aided Design model» 2022. open source code)] to generate reference blade models.

# Reference blade

The **reference blade** is defined with multiple-circular arc profiles[(cite:Crouse_1969_computer)] given in the original NASA report[(cite:moore1973design)]. Corresponding models are computed with the open-source code OpenMCAD[(cite:Kojtych_2022_gene_aubes)].

## Geometry

The geometry of rotor 16 is described in the original NASA report by the following tables. The length are in centimeters and the angles in degrees.

TABLE IV. - BLADE GEOMETRY FOR ROTOR 16

| RP | PERCENT SPAN | RADII RI | RO | BLADE ANGLES KIC | KTC | KOC | DELTA INC | CONE ANGLE |
|---|---|---|---|---|---|---|---|---|
| TIP | 0. | 25.204 | 24.905 | 67.60 | 66.34 | 61.49 | 2.51 | -9.339 |
| 1 | 5. | 24.683 | 24.364 | 66.48 | 65.43 | 60.78 | 2.75 | -9.519 |
| 2 | 10. | 24.123 | 23.824 | 65.30 | 64.30 | 60.02 | 3.00 | -8.557 |
| 3 | 30. | 21.814 | 21.662 | 60.91 | 58.82 | 56.21 | 4.07 | -3.692 |
| 4 | 45. | 20.034 | 20.041 | 57.80 | 54.80 | 51.78 | 4.90 | 0.161 |
| 5 | 48. | 19.733 | 19.771 | 57.28 | 54.09 | 50.84 | 5.04 | 0.819 |
| 6 | 50. | 19.430 | 19.501 | 56.76 | 53.37 | 49.85 | 5.18 | 1.482 |
| 7 | 53. | 19.126 | 19.231 | 56.24 | 52.64 | 48.79 | 5.32 | 2.149 |
| 8 | 55. | 18.821 | 18.960 | 55.72 | 51.89 | 47.68 | 5.46 | 2.817 |
| 9 | 70. | 16.946 | 17.339 | 52.48 | 47.42 | 39.33 | 6.29 | 7.105 |
| 10 | 90. | 14.280 | 15.178 | 47.87 | 41.70 | 21.76 | 7.35 | 13.772 |
| 11 | 95. | 13.570 | 14.637 | 46.64 | 40.42 | 15.40 | 7.59 | 15.655 |
| HUB | 100. | 12.700 | 14.097 | 45.12 | 39.00 | 8.18 | 7.85 | 19.355 |

| RP | BLADE THICKNESSES TI | TM | TO | AXIAL DIMENSIONS ZIC | ZMC | ZTC | ZOC |
|---|---|---|---|---|---|---|---|
| TIP | 0.051 | 0.151 | 0.051 | 1.016 | 1.891 | 2.284 | 2.839 |
| 1 | 0.051 | 0.161 | 0.051 | 0.978 | 1.892 | 2.263 | 2.879 |
| 2 | 0.051 | 0.171 | 0.051 | 0.935 | 1.894 | 2.239 | 2.923 |
| 3 | 0.051 | 0.213 | 0.051 | 0.756 | 1.895 | 2.101 | 3.111 |
| 4 | 0.051 | 0.247 | 0.051 | 0.629 | 1.895 | 1.950 | 3.258 |
| 5 | 0.051 | 0.252 | 0.051 | 0.608 | 1.894 | 1.921 | 3.284 |
| 6 | 0.051 | 0.258 | 0.051 | 0.585 | 1.893 | 1.889 | 3.311 |
| 7 | 0.051 | 0.263 | 0.051 | 0.562 | 1.892 | 1.857 | 3.339 |
| 8 | 0.051 | 0.269 | 0.051 | 0.538 | 1.890 | 1.822 | 3.367 |
| 9 | 0.051 | 0.304 | 0.051 | 0.394 | 1.878 | 1.591 | 3.551 |
| 10 | 0.051 | 0.355 | 0.051 | 0.168 | 1.843 | 1.190 | 3.832 |
| 11 | 0.051 | 0.369 | 0.051 | 0.096 | 1.827 | 1.065 | 3.904 |
| HUB | 0.051 | 0.386 | 0.051 | 0.000 | 1.804 | 0.902 | 3.977 |

## Aerodynamic design

| | unit | values |
|---|---|---|
| **pressure ratio** | [-] | 1.57 |
| **mass flow** | [kg/s] | 26.5 |
| **tip speed** | [m/s] | 425 |
| **tip solidity** | [-] | 1.3 |
| **aspect ratio** | [-] | 2.6 |
| **number of blades** | [-] | 44 |
| **rotative speed** | [rad/s] | 1686 |

## Material properties

The original material of the rotor 16 is not defined in the NASA report. A generic titanium Ti-6Al-4V is considered:

| | unité | valeurs |
|---|---|---|
| **alloy** | [-] | Ti-6Al-4V |
| **Young's modulus** | [GPa] | 108 |
| **density** | [kg/m3] | 4400 |
| **Poisson's ratio** | [-] | 0.34 |
| **yield stress** | [GPa] | 0.824 |

### CAD model

The CAD model is computed with the open source code OpenMCAD[(cite:Kojtych_2022_gene_aubes)].



pressure side



suction side

### Natural frequencies

First three natural frequencies (with clamped root) for the mesh computed with OpenMCAD[(cite:Kojtych_2022_gene_aubes)]:

| Mode | Type | Natural angular frequency (rad/sec) | Natural frequency (Hz) |
|---|---|---|---|
| 1 | 1B | 1456.25 | 231.77 |
| 2 | 2B | 5431.61 | 864.469 |
| 3 | 1T | 7997.11 | 1272.78 |

## Initial blade

The **initial blade** is defined with in-house LAVA parameters[(cite:Kojtych_2022_Methodology)] computed

from the reference blade CAD model. The initial blade is usually used as starting point for an optimization process. Its geometry is similar to the one of the reference blade.

### Natural frequencies

First three natural frequencies (with clamped root)

- from the whole mesh:

| Mode | Type | Natural angular frequency (rad/sec) | Natural frequency (Hz) |
|---|---|---|---|
| 1 | 1B | 1454.87 | 231.55 |
| 2 | 2B | 5429.48 | 864.129 |
| 3 | 1T | 8000.38 | 1273.3 |

- from the reduced order model:

| Mode | Type | Natural angular frequency (rad/sec) | Natural frequency (Hz) |
|---|---|---|---|
| 1 | 1B | 1454.90 | 231.555 |
| 2 | 2B | 5431.53 | 864.455 |
| 3 | 1T | 8002.64 | 1273.66 |

Fichiers téléchargeables
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**Libre accès**

**lien vers le projet Git**

# À propos

Le rotor 16 fait partie d'un programme de recherche visant à étudier l'effet du débit massique par unité de surface annulaire sur les performances des soufflantes à flux axiaux. Une série de trois étages a été conçue, comprenant le rotor 11, 16 et 17 avec un débit massique par unité de surface annulaire de 198, 178 et 208 kilogrammes par seconde par mètre carré. Les trois étages ont été conçus pour produire un rapport de pression de 1,57.

- Rapport technique original [(cite:moore1973design>)]:

```
@TechReport{moore1973design,
  author           = {Moore, R. D. and Urasek, Donald C. and Kovlch,
George},
  date             = {1973},
  institution      = {NASA Lewis Research Center Cleveland, OH, United
States},
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```

```
}
```

- Photographie :

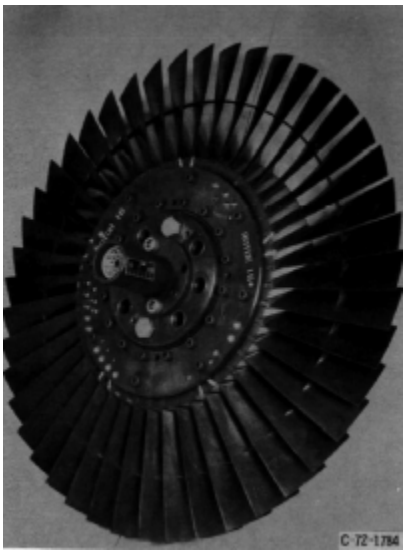


Fig1. https://ntrs.nasa.gov/citations/19740001906 p.64

**Documents utiles**

- modèles téléchargeables (lien vers projet Git)
  - rapport technique original de la NASA (.pdf)
  - fichier de paramètres géométriques (.csv), utilisable en entrée de OpenMCAD[(cite:Kojtych_2022_gene_aubes>)] pour générer l'aube de référence

# Aube de référence

L'**aube de référence** est définie par des profils de type arcs circulaires multiples[(cite:Crouse_1969_computer>Crouse *et al*. «A computer program for composing compressor blading from simulated circular-arc elements on conical surfaces » 1969. NASA-TN-D-5437. pdf)], donnés dans le rapport technique original de la NASA[(cite:moore1973design)]. Les modèles associés sont obtenus avec le code en libre accès OpenMCAD[(cite:Kojtych_2022_gene_aubes)].

## Géométrie

La géométrie du rotor 16 est décrite dans le rapport d'origine de la NASA par les tableaux suivants. Les grandeurs sont en centimètres et en degrés.

TABLE IV. - BLADE GEOMETRY FOR ROTOR 16

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|---|---|---|---|---|---|---|---|---|
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| 2 | 10. | 24.123 | 23.824 | 65.30 | 64.30 | 60.02 | 3.00 | -8.557 |
| 3 | 30. | 21.814 | 21.662 | 60.91 | 58.82 | 56.21 | 4.07 | -3.692 |
| 4 | 45. | 20.034 | 20.041 | 57.80 | 54.80 | 51.78 | 4.90 | 0.161 |
| 5 | 48. | 19.733 | 19.771 | 57.28 | 54.09 | 50.84 | 5.04 | 0.819 |
| 6 | 50. | 19.430 | 19.501 | 56.76 | 53.37 | 49.85 | 5.18 | 1.482 |
| 7 | 53. | 19.126 | 19.231 | 56.24 | 52.64 | 48.79 | 5.32 | 2.149 |
| 8 | 55. | 18.821 | 18.960 | 55.72 | 51.89 | 47.68 | 5.46 | 2.817 |
| 9 | 70. | 16.946 | 17.339 | 52.48 | 47.42 | 39.33 | 6.29 | 7.105 |
| 10 | 90. | 14.280 | 15.178 | 47.87 | 41.70 | 21.76 | 7.35 | 13.772 |
| 11 | 95. | 13.570 | 14.637 | 46.64 | 40.42 | 15.40 | 7.59 | 15.655 |
| HUB | 100. | 12.700 | 14.097 | 45.12 | 39.00 | 8.18 | 7.85 | 19.355 |

| RP | BLADE THICKNESSES TI | TM | TO | AXIAL DIMENSIONS ZIC | ZMC | ZTC | ZOC |
|---|---|---|---|---|---|---|---|
| TIP | 0.051 | 0.151 | 0.051 | 1.016 | 1.891 | 2.284 | 2.839 |
| 1 | 0.051 | 0.161 | 0.051 | 0.978 | 1.892 | 2.263 | 2.879 |
| 2 | 0.051 | 0.171 | 0.051 | 0.935 | 1.894 | 2.239 | 2.923 |
| 3 | 0.051 | 0.213 | 0.051 | 0.756 | 1.895 | 2.101 | 3.111 |
| 4 | 0.051 | 0.247 | 0.051 | 0.629 | 1.895 | 1.950 | 3.258 |
| 5 | 0.051 | 0.252 | 0.051 | 0.608 | 1.894 | 1.921 | 3.284 |
| 6 | 0.051 | 0.258 | 0.051 | 0.585 | 1.893 | 1.889 | 3.311 |
| 7 | 0.051 | 0.263 | 0.051 | 0.562 | 1.892 | 1.857 | 3.339 |
| 8 | 0.051 | 0.269 | 0.051 | 0.538 | 1.890 | 1.822 | 3.367 |
| 9 | 0.051 | 0.304 | 0.051 | 0.394 | 1.878 | 1.591 | 3.551 |
| 10 | 0.051 | 0.355 | 0.051 | 0.168 | 1.843 | 1.190 | 3.832 |
| 11 | 0.051 | 0.369 | 0.051 | 0.096 | 1.827 | 1.065 | 3.904 |
| HUB | 0.051 | 0.386 | 0.051 | 0.000 | 1.804 | 0.902 | 3.977 |

## Caractéristiques aérodynamiques

| | unit | value |
|---|---|---|
| **taux de compression** | [-] | 1,57 |
| **débit massique** | [kg/s] | 26,5 |
| **vitesse en tête** | [m/s] | 425 |
| **solidité en tête** | [-] | 1,3 |
| **allongement** | [-] | 2,6 |
| **nombre d'aubes** | [-] | 44 |
| **vitesse de rotation nominale $\omega_n$** | [rad/s] | 1686 |

## Propriétés matériau

Le matériau original du rotor 16 n'est pas défini dans le rapport de la NASA. Un alliage de titane Ti-6Al-4v est considéré :

| | unit | value |
|---|---|---|
| **alliage** | [-] | Ti-6Al-4v |
| **module d'Young** | [GPa] | 108 |
| **masse volumique** | [kg/m3] | 4400 |
| **coefficient de Poisson** | [-] | 0,34 |
| **limite élastique** | [GPa] | 0,824 |

## Modèle CAO

Le modèle CAO est obtenu avec OpenMCAD[(cite:Kojtych_2022_gene_aubes)].



intrados



extrados

## Fréquences propres

Fréquences des trois premiers modes (noeuds du pied d'aube encastrés) pour le maillage obtenu avec OpenMCAD[(cite:Kojtych_2022_gene_aubes)] :

| Mode | Type | Pulsation propre (rad/sec) | Fréquence propre (Hz) |
|---|---|---|---|
| 1 | 1F | 1456,25 | 231,77 |
| 2 | 2F | 5431,61 | 864,469 |
| 3 | 1T | 7997,11 | 1272,78 |

## Diagramme de Campbell

Évolution des fréquences propres des 3 premiers modes, en fonction de la vitesse de rotation, pour le maillage obtenu avec OpenMCAD[(cite:Kojtych_2022_gene_aubes)]:

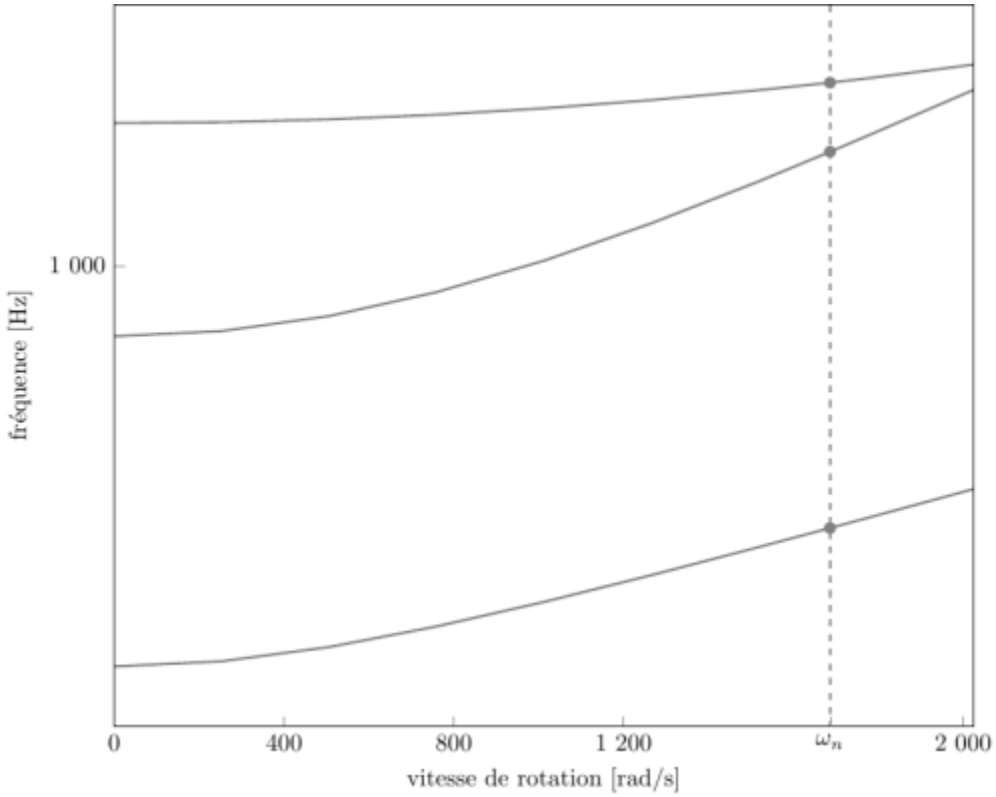



diagramme de Campbell calculé avec une précharge centrifuge linéaire, noeuds du pied d'aube encastrés (vitesse nominale $\omega_n$ = 1 686 rad/s)

- graphique (.pdf)
- données du Campbell (.csv)

# Aube initiale

L'**aube initiale** est définie par des paramètres spécifiques au LAVA[(cite:Kojtych_2022_Methodology>Kojtych S. *et al*. «Methodology for the Redesign of Compressor Blades Undergoing Nonlinear Structural Interactions: Application to Blade-Tip/Casing Contacts » 2022. Journal of Engineering for Gas Turbines and Power, Vol. 145, No. 5. pdf)] obtenus à partir du modèle CAO de l'aube de référence. L'aube initiale est classiquement utilisée comme point de départ dans le cadre de procédures d'optimisation; sa géométrie est similaire à celle de l'aube de référence.

## Fréquences propres

Fréquences des trois premiers modes (noeuds du pied d'aube encastrés),

- pour le maillage complet :

| Mode | Type | Pulsation propre (rad/sec) | Fréquence propre (Hz) |
|---|---|---|---|
| 1 | 1F | 1454,87 | 231,55 |
| 2 | 2F | 5429,48 | 864,129 |
| 3 | 1T | 8000,38 | 1273,3 |

- pour le modèle réduit :

| Mode | Type | Pulsation propre (rad/sec) | Fréquence propre (Hz) |
|---|---|---|---|
| 1 | 1F | 1454,90 | 231,555 |
| 2 | 2F | 5431,53 | 864,455 |
| 3 | 1T | 8002,64 | 1273,66 |

Document issu de la page wiki:
**https://wiki.lava.polymtl.ca/public/modeles/rotor_16/accueil?rev=1722004796**

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