THE METHOD OF AVERAGE FLOW PARAMETERS EVALUATION

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ABSTRACT

This paper deals with average flow parameters evaluation on annular cascades by method which is used at Czech Aeronautical Research and Test Institute. Methodology comes out from test facility design and applied measurement procedure. To decrease wall proximity effects there is not used multi-hole pressure probe but three separated probes for 3D flow parameters determination.

INTRODUCTION

Investigation of flow field parameters on annular cascades has some theoretical advantages in comparison with doing it on linear cascades. Annular cascade is encircled so there are no problems with periodicity of flow field. Passage is in the first principle three dimensional and there is no need to make corrections that are necessary in case of linear cascades. Nevertheless there are extensive problems with experimental setup. From theoretical point of view, annular cascade looks like statistical set of exactly known number of inaccurate channels the dimensions of which are various from an average dimensions. In the case discussed below there is different flow field in each channel, so it's not enough to measure only one or two channels for application to whole wheel. On the other side, whole cascade measurement grants conclusive result, however with heavy costs. So, experimentalist is pressed to choose appropriate compromise.

NOMENCLATURE

a .... [m/s] .... sonic velocity
E ... . mean reduced kinetic energy
i, j, k, m........... index variables
n0.. .... total number of points on one radius
n1.. .... number of blades in wheel
n2.. .... number of points in unified channel
n3.. .... number of averaged channels
p.... [Pa].......... pressure
q.... .... local reduced flow density
Q... .... mean reduced mass flow
r .... [mm]........ radius
R ... [J/kg/K] ... universal gas constant
S.... .... mean reduced entropy
T.... [K]........... temperature
v .... [m/s]......... local velocity
V ... [m/s]......... mean velocity
α.... [°]............ yaw angle
β.... [°]............ pitch angle
ζ.... .... pressure loss coefficient
η.... .... energy loss coefficient
κ.... .... ratio of specific heats
ρ.... [kg/m^3]..... density

Subscripts
0 ....total condition
1 ....inlet condition
2 ....outlet condition
a ....axial
is........isentropic
r ....radial
ref......reference condition
t ....tangencial
* ....critical condition

AVERAGING TO REPRESENTATIVE CHANNEL

Channels geometry could be reciprocally different in percents of pitch. It comes from cascade design and technology of production. An easy way to eliminate differences between flow field images of individual channels is averaging many passages flow parameters. It is not decisive behind which blades measurement runs, because average value must be the same in all cases. If we estimate deviations in two adjacent passages in percents, then average value of any parameter checked in ten adjacent channels will be different in per mille from average checked in the other selection of ten channels. This consideration licenses us to measure only a part of wheel and moreover, the first parameter we can measure in one selection of vanes, the second in the other and so on. Series of vanes overlaps only partly.

In order to reduce interference effects are used three separated pressure probes in our investigation. The first one is the Pitot-static probe for total and static pressure determination. Next two probes are directional for pitch and yaw angle determination.

Certainly there are some space requirements around probe motional mechanisms, therefore probes are each another angularly distanced by 60°.

All of the three probes are extended at the same radius, turned to the same angle and their angular distances are constant.

The average flow parameter image is obtained by thereinafter way. Probes are traversed along arcs on several radiuses through approximately ten blades. Information from each probe form data with coordinates from which are determined points in the first angled pitch. Then at each point in the first pitch the average value is computed from points with distances equal to integer multiple of pitch. Our facility setup is represented by 900 measured points at 360°, so two adjacent points are angularly distanced by 0,4°. Average values are computed by this equation:

$$p(i,\ k) = \frac{1}{n3} \cdot \sum_{j} p(i + INT(j\frac{900}{n1}),\ k),$$

i changes from 1 to n2
j changes from 0 to n3-1
k changes from 1 to 3
n2 = 1 + INT(900/n1)
n3 = INT(n0/900/n1)
p(i, k) – averaged pressure at point *i* from probe *k*

By this equation average values are computed at each point in unified channel for all three probes at all measured radiuses. A problem appears if probe pitch divided by blade pitch is not integer value. In this case, data in matrixes must be moved, because data from probes do not match to the same position in unified channel. At the beginning of doing it we choose reference probe whose position is not changed and the others are synchronized to it.

In our case the pitot-static probe is chosen as reference probe, so yaw angle probe is distanced by H(2) angle and pitch angle probe by H(3) angle from the pitot-static probe. Relative position in unified channel is shown at Fig. 1. The assumption for pitot-static probe is, that the point with index i=1 is at beginning of blade pitch and point i=n2 is at the end of blade pitch. Other probes are relatively distanced by integral multiple of pitch and a fraction of pitch from the pitot-static probe. Fraction of pitch is the value that is interesting for us and it is computed in point units by this equation:

$$F(k) = INT\left[\left(H(k) - INT\left(\frac{H(k)}{\frac{360}{n1}}\right) \cdot \frac{360}{n1}\right) \cdot 2{,}5\right],$$

where *k* changes from 2 to 3

Then it is necessary to select angle probes points that match to pitot-static probe points. If pitot-static point has index *i*, then angle probe point has index m:

If $i + F(k) < 1 \quad or \quad i + F(k) > n2$,
then

$$m(k) = i + F(k) - \frac{|i + F(k)|}{i + F(k)} \cdot n2,$$

else

$$m(k) = i + F(k).$$

Doing this the data from pressure probes are correctly arranged in the representative channel. According to the calibration of pressure probes flow parameters are computed and we can continue to the next step.

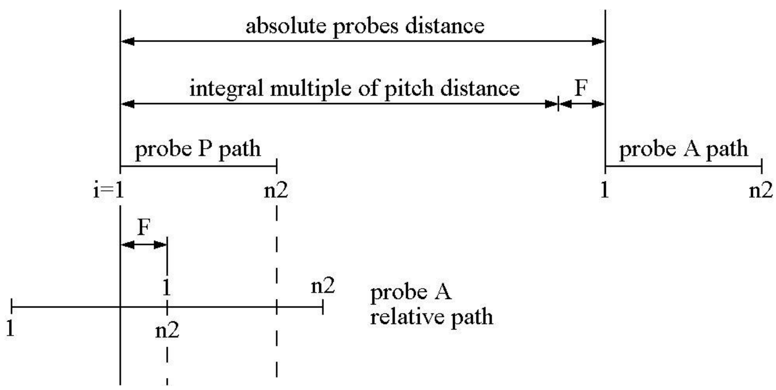

Fig. 1 Relative position of probes in unified channel

AVERAGE FLOW PARAMETERS EVALUATION

The methodology is based on the fact that it is not possible to meet all physical conservation principles in determination of average flow parameters. Therefore suitable criteria were chosen. These criteria ensure that real and idealized averaged flow parameters have identical sum of enthalpy, entropy and momentum in investigated area. System is completed with law of conservation of matter and assumption of isentropic expansion.

Local density, velocity, momentum, enthalpy and entropy are computed at each point. Energy and pressure losses will be finally computed in comparison with initial conditions that are simultaneously observed. In the next step all values are integrated through whole area and captured values divided by this area.

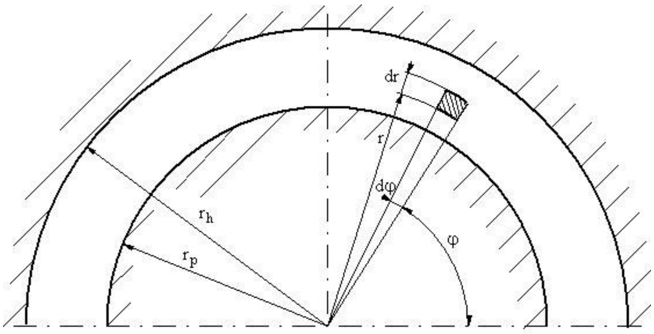

Fig. 2 Aerial element in traversing plane

$$A = \iint_S dS = \iint r \, d\varphi \, dr$$

Dividing integrals by the area provides weighted averages of measured values.

In all equations reduced values are used. Velocity and its components are reduced by the critical air velocity as folows

$$a_* = \sqrt{\frac{2 \cdot \kappa}{\kappa} \cdot R \cdot T_{0ref}} \; .$$

The total temperature at the inlet of cascade T_{0ref} is measured simultaneously with the total pressure p_{0ref}. These parameters vary slightly during the measurement that takes approximately an hour. Of course, proportionally to these changes absolute value of all parameters varies. This is the reason to use reduced values, whose variations are negligible. Pressure and temperature reference values are averaged from whole measurement and for one regime are used these values as constants:

$$p_{01} = \frac{1}{N} \sum_{i=1}^{N} p_{0ref\,i} \; ,$$

$$T_{01} = \frac{1}{N} \sum_{i=1}^{N} T_{0ref\,i} \; .$$

Then deduced comparing value is density in reference conditions

$$\rho_{01} = \frac{p_{01}}{R \cdot T_{01}} \; .$$

To simplify the situation, possible assumption to deduce next equations is adiabatic flow through cascade. These equations were obtained to flow parameters computation.

At first the mass flow in direction perpendicular to plane of traversing is computed

$$Q = \left(\frac{\rho \cdot v}{\rho_{01} \cdot a_*} \right)_a = \frac{1}{A} \cdot \iint_S \left(\frac{\rho_i \cdot v_i}{\rho_{01} \cdot a_*} \right)_a dS =$$
$$= \frac{1}{A} \cdot \iint_S q_i \; dS$$

where q_i is relative flow density in axial direction

$$q_i = \frac{\rho_i \cdot v}{\rho_{01} \cdot a_*} \cdot \sin \alpha_i \cdot \cos \beta_i \, .$$

Subsequently the energy

$$E = \left(\frac{\rho \cdot v}{\rho_{01} \cdot a_*} \right)_a \cdot \frac{v^2}{a_*^2} = \frac{1}{A} \cdot \iint_S q_i \cdot \frac{v_i^2}{a_*^2} \, dS \; ,$$

entropy

$$S = \left(\frac{\rho \cdot v}{\rho_{01} \cdot a_*} \right)_a \cdot \ln \frac{p_{02}}{p_{01}} =$$
$$= \frac{1}{A} \cdot \iint_S q_i \cdot \ln \frac{p_{02\,i}}{p_{01}} \, dS$$

tangential momentum

$$H_t = \left(\frac{\rho \cdot v}{\rho_{01} \cdot a_*} \right)_a \cdot \frac{v}{a_*} \cdot \cos \alpha_2 \cdot \cos \beta_2 =$$
$$= \frac{1}{A} \cdot \iint_S q_i \cdot \frac{v_i}{a_*} \cdot \cos \alpha_{2i} \cdot \cos \beta_{2i} \; dS$$

radial momentum

$$H_r = \left(\frac{\rho \cdot v}{\rho_{01} \cdot a_*} \right)_a \cdot \frac{v}{a_*} \cdot \cos \beta_2 =$$
$$= \frac{1}{A} \cdot \iint_S q_i \cdot \frac{v_i}{a_*} \cdot \cos \beta_{2i} \; dS$$

and axial momentum

$$H_a = \left(\frac{\rho \cdot v}{\rho_{01} \cdot a_*} \right)_a \cdot \frac{v}{a_*} \cdot \sin \alpha_2 \cdot \cos \beta_2 =$$
$$= \frac{1}{A} \cdot \iint_S q_i \cdot \frac{v_i}{a_*} \cdot \sin \alpha_{2i} \cdot \cos \beta_{2i} \; dS$$

can be computed.

Areal integration of each parameter is solved numerically with modified Simpson's 2D method for integration in cylindrical coordinates. It is appropriate to use this method for an application on a sector of measured channel with discretely distributed parameters. The only limitations of this method are requirements of uniform steps at coordinates and odd number of measured points. This is not barrier, because all of these requirements can be easily kept.

The mean velocity vector from system of equations is computed

$$\frac{V}{a_*} = \sqrt{\frac{E}{Q}},$$

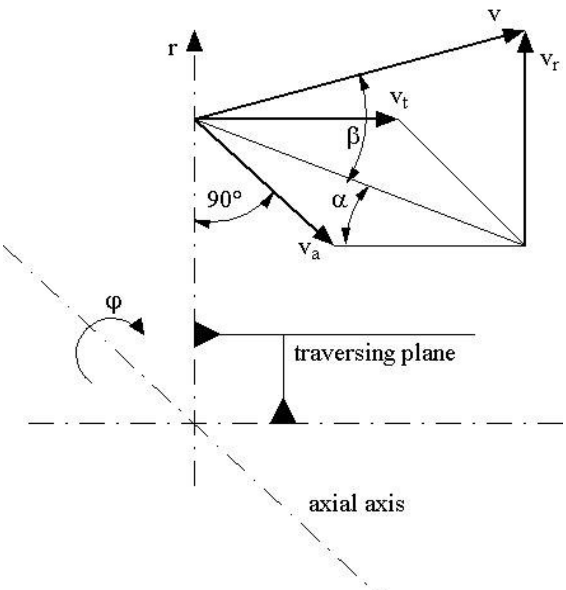

Fig. 3 Outlet velocity component orientations

consecutively flow directions (Fig. 3) are evaluated at the outlet of cascade

$$\alpha_2 = arctg\left(\frac{H_a}{H_t}\right)$$

$$\beta_2 = arctg\left(\frac{H_r \cdot \cos\alpha_2}{H_t}\right).$$

Pressure loss coefficient is defined as

$$\varsigma = \frac{p_{01} - p_{02}}{p_{01}} = 1 - \exp\left(\frac{S}{Q}\right).$$

To mean velocity V/a_* corresponds pressure ratio

$$\frac{p_2}{p_{02}} = \left[1 - \frac{\kappa - 1}{\kappa + 1} \cdot \left(\frac{V}{a_*}\right)^2\right]^{\frac{k}{k-1}}$$

and isentropic pressure ratio

$$\frac{p_2}{p_{01}} = \frac{p_2}{p_{02}} \cdot \frac{p_{02}}{p_{01}},$$

from which is computed isentropic expansion velocity

$$\frac{V_{is}}{a_*} = \sqrt{\frac{\kappa + 1}{\kappa - 1} \cdot \left(1 - \left(\frac{p_2}{p_{01}}\right)^{\frac{k-1}{k}}\right)}.$$

The last interesting parameter is kinetic energy loss coefficient that is defined as

$$\eta = 1 - \frac{V^2}{V_{is}^2}.$$

CONCLUSION

The methodology proposed for annular cascade measurement comes from design of test facility that is fitted with three angularly distanced pressure probes. The argument for this adjustment is decreasing interference effects of probes. The probes are guided along the supports which are placed along the whole height of the channel. Therefore, the front profile is constant regardless on radius position of probes and impact on flow is constant for all positions.

The problem of probe distances is solved indirectly on a base of existence of average flow parameters image. If there is this image of flow parameters, there is chance to detect it from random section of wheel. So it is possible to measure each parameter with one probe and the parameters from different probes put together for getting whole flow parameters image.

The recounting of flow parameters distribution is done through sum of mass flow, momentum and energy with condition of isentropic expansion that relates to representative pressures and velocity. The output is one mean velocity whose determination is based on the kinetic energy conservation law and two mean static pressures from conditions of energy conservation and momentum conservation.

The method of measurement and evaluation was verified by measurement of three cascades. The first one was a first stage stator of a turboprop engine, where outlet velocity was about Mach number 1, and the others were steam turbine cascades with outlet Mach number 2. The basic part of verification was to check required number of measured channels. It is possible to say that 6 channels are enough for measurement, but for getting more accurate results, it's necessary to check this number by statistical analysis. Therefore whole wheel is traversed at important regimes at the beginning of work. Then the statistical analysis is made, selection of vanes with no big defects is chosen and count of channels that is indispensable to measure is solved. Comparison of three probes measurement method with multihole probe measurement is currently solved.

ACKNOWLEDGMENTS

The support of this project from the Ministry of Education, Youth and Sports under the grant No MSM 0001066902 is gratefully acknowledged.

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