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DATA REDUCTION METHODS IN TURBOMACHINERY LINEAR BLADE CASCADE EXPERIMENT

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Abstract

The work explores data reduction methods used in turbomachinery linear blade cascade experiment, such as area and mass averaging and Two-Dimensional Momentum Method, and their properties. Definitions of the most common methods are listed and the methods are tested on data sets acquired experimentally and also numerically. Differences in important characteristics of the blade cascade, such as kinetic energy loss coefficient, total pressure loss coefficient, or outlet angle, obtained by different methods are reported together with the change of conservative fluxes caused by reduction of the data. Information on the data reduction methods used by selected European research groups is provided.

Keywords: data reduction method, turbomachinery, cascade

Nomenclature

Greek

α_2	outlet angle [°]
γ	heat capacity ratio [1]
η	tangential (pitchwise) coordinate [m]
ϕ	general variable
ξ	kinetic energy loss coefficient [1]
ρ	density [kg/m^3]
ω	total pressure loss coefficient [1]

Latin

c_p	specific heat at constant pressure [J/(kg·K)]
I_A	mean momentum flux in axial direction [kg/(m·s^2)]
I_C	mean momentum flux in tangential direction [kg/(m·s^2)]
I_H	mean enthalpy flux [kg/(m^2·s)]
I_M	mean mass flux [kg/(m^2·s)]
I_S	mean entropy flux [kg/(s^4·K)]
M	Mach number [1]
M*	dimensionless velocity, Laval number [1]
p	static pressure [Pa]
r	specific gas constant [J/(kg·K)]
T	temperature [K]
t	pitch [m]
$\mathbf{w}$	vector of velocity [m/s]
z/H	normalized spanwise location [m]

Abbreviations and Indices

$_0$	total
$_1$	inlet
$_2$	outlet
A	area weighted averaging
MM	Data Reduction Method
$\dot{m}$	mass flow weighted averaging
MM	momentum method
VZLU	method used at Czech Aerospace Research Centre

1 Introduction

Linear blade cascades, turbine and compressor, have been a popular object of the turbomachinery experiment for decades. The elementary results reported consist of values of kinetic energy loss coefficient ξ, total pressure loss coefficient ω, pressure ratio ${}^{p_2}/_{p_1}$, outlet angle α_2, etc. As the flow field within the measurement space is far from homogeneous, these values cannot be calculated directly and the measured data, usually obtained by traversing in tangential (pitchwise) direction, need to be reduced.

Generally, any data reduction method (DRM) studied in this work can be understood as an operator that converts a vector of states $\mathbf{X}(\mathbf{x_i} = [\rho_i, T_i, p_i, p_{0i}.w_{xi}, w_{yi}])$ into a single representative state $\langle\mathbf{x}\rangle = [\langle\rho\rangle, \langle T\rangle, \langle p\rangle, \langle p_0\rangle, \langle w_x\rangle, \langle w_y\rangle]$, $\mathcal{R} : \mathbf{X} \mapsto \langle\mathbf{x}\rangle$. Typically, data are assumed to be periodical with the period equal to the pitch of the cascade t. Different DRMs used in turbomachinery can lead to different results, making the reported values incomparable, especially in cases where the DRM is not specified.

DRMs can be divided into two families: averaging and mixing (ideally conservative) methods. Averaging methods are, as the name suggests, based on weighted averaging of quantities of interest. Mixing methods are usually defined with a physical conception of a mixing process with a goal of conserving given quantities, typically fluxes of conservative variables. An AGARDoghraph [1, pp. 14-19], focused on testing of turbomachinery components, lists several averaging methods and one of mixing type, Two-Dimensional Momentum Method, which, reportedly, ensures conservation of mass, momentum and energy flux. Theoretically, its results are independent of position of measurement planes. A method based on Two-Dimensional Momentum Method expanded for non-homogeneous flows is documented in [2]. Strictly conservative DRM is described in [3].

From the point of view of CFD, the reduction methods are comparable to methods applied to a so-called mixing plane boundary condition used for simulation of steady, time averaged flows in regions in relative motion (for example stator-rotor interaction). While in CFD the mixing methods that preserve fluxes are generally considered superior [4], in experiment the simple weighted averaging methods are usually preferred.

In this work DRMs are listed and analyzed on selected sets of experimental and numerical data. Mass, momentum, enthalpy, and entropy production are reported for each of the studied methods along with differences in kinetic energy loss coefficient ξ or total pressure loss coefficient ω (for turbine or compressor cascades, respectively), outlet angle α_2 and Mach number M_2 obtained from reduced data.

1.1 Weighted Averaging methods

DRMs based on weighted averaging of traversing data can generally be used for any variable of a tangential (pitchwise) coordinate $\phi(\eta)$, resulting in an average value $\langle\phi\rangle$.

Area Averaging method is defined by

$$\langle\phi\rangle_A = \frac{1}{t}\int_0^t \phi(\eta)\,\mathrm{d}\eta, \tag{1}$$

which is apparently the simplest reduction method used. As the traversing data are usually obtained with constant sampling, the integration becomes a simple sum multiplied by pitch t.

Mass Averaging method is defined as

$$\langle\phi\rangle_{\dot m} = \frac{\displaystyle\int_0^t [\rho(\eta)\,w_x(\eta)\,\phi(\eta)]\,\mathrm{d}\eta}{\displaystyle\int_0^t [\rho(\eta)\,w_x(\eta)]\,\mathrm{d}\eta}. \tag{2}$$

Momentum Averaging is, according to [1], based on equation

$$\langle||\mathbf{w}||\rangle_{MOM}\int_0^t [\rho(\eta)\,w_x(\eta)]\,\mathrm{d}\eta = \int_0^t [||\mathbf{w}(\eta)||\,\rho(\eta)\,w_x(\eta)]\,\mathrm{d}\eta \tag{3}$$

This equation complies with mass averaging of velocity $||\mathbf{w}||$ according to (2). The difference is in the computation of the total pressure p_0, which is, according to [1], with Momentum averaging obtained from an isentropic Mach number relation, where the static pressure is taken as an area average $\langle p\rangle_A$. Similarly, the **Enthalpy averaging** and **Entropy averaging** methods are defined, but as the definitions in relevant literature do not explicitly specify the way other quantities, such as α_2, are obtained, they are not studied further.

Mass averaging method is usually used in *Turbine Department of Institute of Fluid-Flow Machinery, Polish Academy of Sciences* rather than area averaging for determination of enthalpy and total pressure losses in turbines. It is also used at *Department of Fan and Compressor, Institute of Propulsion Technology, German Aerospace Center* for reduction of 2D data.

Turbine Research Expertise Group at the von Karman Institute for Fluid Dynamics uses a combination of Area and Mass Averaging. Static pressure is weighted by area, whereas total quantities, such as total pressure are weighted by mass flux. Quantity defined as a combination of flow variables is computed from already reduced values. An example of such quantity is the kinetic energy loss coefficient in which outlet static, inlet and outlet total pressures are combined [5, p. 2-48].

1.2 Conservative methods

Two-Dimensional Momentum Method (MM) is according to [2] based on conservation of mean mass (I_M), momentum (I_A and I_C) and energy fluxes. The relation (4b) can also be viewed as a constraint for axial force equilibrium. With assumption of constant total temperature T_0 and fluid being an ideal gas, the representative values of variables can be obtained from the set of equations:

$$I_M = \frac{1}{t}\int_0^t [\rho(\eta)\, w_x(\eta)]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{MM}}\langle w_x\rangle_{\mathrm{MM}} \tag{4a}$$

$$I_A = \frac{1}{t}\int_0^t \left[\rho(\eta)\, w_x(\eta)^2 + p(\eta)\right]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{MM}}\langle w_x\rangle^2_{\mathrm{MM}} + \langle p\rangle_{\mathrm{MM}} \tag{4b}$$

$$I_C = \frac{1}{t}\int_0^t [\rho(\eta)\, w_x(\eta) w_y(\eta)]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{MM}}\langle w_x\rangle_{\mathrm{MM}}\langle w_y\rangle_{\mathrm{MM}} \tag{4c}$$

$$\langle w_y\rangle^2_{\mathrm{MM}} + \langle w_y\rangle^2_{\mathrm{MM}} = 2c_p(T_0 - \langle T\rangle_{\mathrm{MM}}) \tag{4d}$$

$$\langle p\rangle_{\mathrm{MM}} = \langle\rho\rangle_{\mathrm{MM}}\, r\, \langle T\rangle_{\mathrm{MM}} \tag{4e}$$

The set of equations (4) leads to quadratic equation and the root needs to be carefully chosen [2]. This method is used at the *Laboratory of Internal Flows, IT CAS*. Also it is used at *Department of Fan and Compressor, Institute of Propulsion Technology, German Aerospace Center* for reduction of 1D data.

Strictly Conservative Method is described in [3]. Mean flux of momentum in axial direction is defined differently than in (4b), in accordance with classical physical concept of a flux. Mean fluxes of enthalpy and entropy (I_H and I_S, respectively), with assumption of stationary adiabatic flow [6], are added.

$$I_M = \frac{1}{t}\int_0^t [\rho(\eta)\, w_x(\eta)]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{VZLU}}\langle w_x\rangle_{\mathrm{VZLU}} \tag{5a}$$

$$I_A = \frac{1}{t}\int_0^t \left[\rho(\eta)\, w_x(\eta)^2\right]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{VZLU}}\langle w_x\rangle^2_{\mathrm{VZLU}} \tag{5b}$$

$$I_C = \frac{1}{t}\int_0^t [\rho(\eta)\, w_x(\eta) w_y(\eta)]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{VZLU}}\langle w_x\rangle_{\mathrm{VZLU}}\langle w_y\rangle_{\mathrm{VZLU}} \tag{5c}$$

$$I_H = \frac{1}{t}\int_0^t \left[\rho(\eta)\, w_x(\eta)\left(\frac{p(\eta)}{p_0(\eta)}\right)^{\frac{\gamma-1}{\gamma}}\right]\, \mathrm{d}\eta = \langle\rho\rangle_{\mathrm{VZLU}}\langle w_x\rangle_{\mathrm{VZLU}}\langle \frac{p}{p_0}\rangle^{\frac{\gamma-1}{\gamma}}_{\mathrm{VZLU}} \tag{5d}$$

$$I_S = r\,\frac{1}{t}\int_0^t \left[\rho(\eta)\, w_x(\eta)\ln\left(\frac{\langle p_{01}\rangle_A}{p_0(\eta)}\right)\right]\, \mathrm{d}\eta = r\,\langle\rho\rangle_{\mathrm{VZLU}}\langle w_x\rangle_{\mathrm{VZLU}}\langle \ln\frac{\langle p_{01}\rangle_A}{p_0}\rangle_{\mathrm{VZLU}} \tag{5e}$$

Based on the set of equations (5) with the same assumptions as for Momentum Method we obtain:

$$\langle p_{02}\rangle_{\mathrm{VZLU}} = \langle p_{01}\rangle_A\, e^{-\frac{1}{r}\frac{I_S}{I_M}} \tag{6a}$$

$$\langle T_2\rangle_{\mathrm{VZLU}} = T_0\frac{I_H}{I_M} \tag{6b}$$

$$\langle \alpha_2\rangle_{\mathrm{VZLU}} = \arctan\frac{I_C}{I_A} \tag{6c}$$

$$\langle p_2\rangle_{\mathrm{VZLU}} = T_0\left(\frac{I_H}{I_M}\right)^{\frac{\gamma}{\gamma-1}} \tag{6d}$$

This method is used by *Laboratory of High-Speed Aerodynamics, Czech Aerospace Research Centre.* By definition $\langle\alpha_2\rangle_i$ is equal for mass averaging and VZLU approach.

It is evident, but still certainly worth pointing out, that operations performed within data reduction in gas dynamics are not necessarily commutative. It makes a difference if we first determine the mean pressure and the mean total pressure and then, from the averaged values, we compute Mach number, or if we compute local Mach number and then average it. In our implementation, if the method is not specific about reduction of any quantity, it is computed from already reduced data, e.g. $\langle \mathrm{Ma}\rangle_i = \mathrm{Ma}(\langle p\rangle_i, \langle p_0\rangle_i)$.

2 Results

The DRMs were tested on several test cases, all obtained with air ($\gamma = 1.4$, $r = 287.1$):

Schreiber84 - rotor blade element of a transonic research compressor [7]. Data were extracted from results of in-house - 2D periodic - numerical simulations performed employing an implicit coupled solver described in [8] implemented within the OpenFOAM library [9]. This test case allows for comparison of methods without any disturbance caused by violation of the periodicity of the flow. For one of the regimes (M_1=1.18) the traversing plane passed through a region of large separation and the data are slightly spoiled. This regime is chosen to highlight the behaviour of the methods.

Kobra - compressor first stage rotor tip section, is based on an in-house experiment. The cascade is described in [10]. Inlet Mach number $\mathrm{M}_1 \approx 0.8$, but each of the five tested regimes has a different inlet angle.

SPLEEN - Low Pressure High Speed Turbine Cascade, is an open access database [11] described in [12, 13]. It was chosen for the low Reynolds conditions achieved by the decrease of p_{01}. Good periodicity of the flow field is reported. All regimes were measured at zero incidence. From this database not only midspan data, but also those obtained at 1 % of span (z/H = 1 %) were reduced to asses the influence of the planarity of the flow on the differences between the DRMs.

TRW2 - central section of turbine rotor blade with transonic line, in-house data obtained at atmospheric inlet total pressure and zero incidence, outlet Mach number $\mathrm{M}_2 \in (0.6, 1.7)$. This data were chosen as an estimate based on Hölder's inequality shows that the upper limit of entropy production by Mometum method depends on gradient of entropy in the traversing data. Here the gradient is caused by the intersection of the traversing plane and an oblique shock wave.

The data are reduced by the methods listed in the Introduction. Outlet angle $\langle\alpha_2\rangle_i$, the outlet Mach number $\langle \mathrm{M}_2\rangle_i$ and kinetic energy loss coefficient $\langle\xi\rangle_i$

$$\langle\xi\rangle_i = 1 - \frac{\langle \mathrm{M}_2^*\rangle_i^2}{\langle \mathrm{M}_{2is}^*\rangle_i^2} = 1 - \frac{1 - \left(\frac{\langle p\rangle_i}{\langle p_0\rangle_i}\right)^{\frac{\gamma-1}{\gamma}}}{1 - \left(\frac{\langle p\rangle_i}{\langle p_{01}\rangle_i}\right)^{\frac{\gamma-1}{\gamma}}} \tag{7}$$

for turbine cascades and total pressure loss coefficient $\langle\omega\rangle_i$

$$\langle\omega\rangle_i = \frac{\langle p_{01}\rangle_i - \langle p_{02}\rangle_i}{\langle p_{01}\rangle_i - \langle p_1\rangle_i} \tag{8}$$

for the compressor ones[1] given by each method are compared (an explanatory matrix (a key) is shown in Fig. 1)

The relative error of the fluxes $({}^{I_j}/{}_{I_{j\mathrm{true}}} - 1)\cdot 100[\%], j \in \{M, A, C, H, S\}$, where I_j is a flux calculated from reduced values and $I_{j\mathrm{true}}$ is obtained by integrating the original data. Relations (5b) are used for the computation of I_A and $I_{A\mathrm{true}}$.

The results are shown in Figs. 2, 3, 4 and 5. Each row of matrices is dedicated to one regime. The first three matrices in each row compare α_2, M_2 and ξ or ω for turbine or compressor cascades, respectively. The last matrix in each row shows the relative errors in fluxes. The colors used in the figures are selected to represent relative differences, values larger than the average / true ones

[1]For data except SPLEEN, inlet total pressure for calculation of ξ and ω is assumed constant $p_{01}(\eta)$=const.

are highlighted in red, the lower ones in blue. In the matrices comparing fluxes the color scale is constant and the full opacity is reached at ±10 % error, in the others the scale is relative to the tested regime.

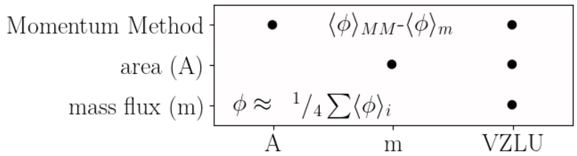

Figure 1: A key for comparison matrices

The two problematic data sets (SPLEEN: z/H=1% and Schreiber84: M_1=1.10) proved to be a weak point of the DRMs. Where the method allows it, the conservative fluxes are biased.

Differences between resulting Mach numbers are negligible in most cases. On the other hand, differences in outlet angle in an order of one tenth of a degree even for numerical and therefore nearly perfectly planar and periodic data should raise at least a slight concern.

Generally, most noticeable entropy production can be assigned to area averaging and Momentum Method. In most cases the entropy production by mass weighted averaging is negative, which is against the second law of thermodynamics, but mass averaging does not claim to be physically supported. Apparently, the supersonic regimes of TRW2 support the estimate of the link between the presence of large gradients in the data and the entropy production by Momentum Method. The entropy production by reduction strongly influences the resulting loss coefficients. Considering the physical background of the Momentum Method, the homogenization by mixing, the entropy production may not be viewed as a pure deficiency. Differences in other - conservative - fluxes are, for cases aligned with blade cascade experiment assumptions, nearly negligible.

3 Conclusions

Data reduction methods used in linear blade cascade experiment were tested. Two of the tested methods are based on weighted averaging and two on conservation of fluxes. The methods were tested on several geometries, including both compressor and turbine blade cascades, with different regimes imposed.

No right, preferable, or superior method can be chosen. Each of the methods has its own advantages and disadvantages. The goal of this work is to highlight the need to report on the DRM used if any reduced data are communicated. This recommendation holds not only for experimental results, but also for numerical ones.

Regarding this, the indisputable advantage of more complex method like Momentum Method is that it explicitly defines the way dependent variables are computed, while for weighted averages this is usually not the case. While once the Momentum Method is referred, any other raw data are easily comparable to the reduced results, reference to any of the averaging methods is not enough, and the order of operations should be stated.

"In-house" data, their preprocessing and implementation of the studied data reduction methods can be found in a dedicated GitHub repository (*github.com/kreuzter/reductionMethods*).

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Schreiber84: $\mathrm{Ma}_1 = 0.95$; $p_{01} = 1.0{\cdot}10^5$ Pa; $\alpha_1 = 8.5°$; z/H = 50 %

0.103	0.100	0.100	-0.001	-0.002	-0.002	-0.001	0.002	0.001
	-0.003	-0.003		-0.002	-0.001		0.003	0.002
$\alpha_2 \approx$	39.473°	0.000	$M_2 \approx$	0.555	0.000	$\omega \approx$	0.032	-0.000

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.355	0.000	0.042	4.602
area	-0.030	-0.337	-0.346	-0.002	7.643
mass flux	0.316	0.316	0.316	0.308	-1.248
VZLU	0.000	0.000	0.000	0.000	-0.000

Schreiber84: $\mathrm{Ma}_1 = 1.03$; $p_{01} = 1.9{\cdot}10^5$ Pa; $\alpha_1 = 10.0°$; z/H = 50 %

0.196	0.195	0.195	-0.002	-0.005	-0.004	-0.002	0.003	0.002
	-0.001	-0.001		-0.003	-0.003		0.005	0.004
$\alpha_2 \approx$	38.537°	0.000	$M_2 \approx$	0.601	0.001	$\omega \approx$	0.047	-0.001

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.694	0.000	0.092	5.288
area	-0.060	-0.636	-0.640	-0.004	9.218
mass flux	0.592	0.592	0.592	0.577	-1.276
VZLU	0.000	0.000	0.000	0.000	-0.000

Schreiber84: $\mathrm{Ma}_1 = 1.10$; $p_{01} = 1.0{\cdot}10^5$ Pa; $\alpha_1 = 13.0°$; z/H = 50 %

1.719	1.579	1.579	-0.012	-0.030	-0.026	-0.016	0.013	0.007
	-0.141	-0.141		-0.018	-0.014		0.028	0.023
$\alpha_2 \approx$	41.349°	0.000	$M_2 \approx$	0.673	0.004	$\omega \approx$	0.114	-0.005

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-5.395	-0.000	0.629	7.016
area	0.908	-2.120	-2.604	1.255	23.108
mass flux	4.512	4.512	4.512	4.399	-0.658
VZLU	0.000	0.000	-0.000	0.000	0.000

Schreiber84: $\mathrm{Ma}_1 = 1.18$; $p_{01} = 1.0{\cdot}10^5$ Pa; $\alpha_1 = 8.5°$; z/H = 50 %

0.255	0.249	0.249	-0.002	-0.006	-0.005	-0.002	0.004	0.003
	-0.006	-0.006		-0.004	-0.003		0.006	0.005
$\alpha_2 \approx$	40.807°	-0.000	$M_2 \approx$	0.598	0.001	$\omega \approx$	0.057	-0.001

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.873	0.000	0.114	5.096
area	-0.076	-0.816	-0.837	-0.002	8.421
mass flux	0.766	0.766	0.766	0.743	-1.133
VZLU	0.000	0.000	0.000	0.000	-0.000

Figure 2: Comparison of Data Reduction Methods on compressor Schreiber84 testcase

Kobra: $\mathrm{M}_1 = 0.802$, $p_{01} \approx 0.984{\cdot}10^5$ Pa; $\alpha_1 = 57.7°$; z/H = 50 %

0.319	0.311	0.311	-0.001	-0.006	-0.005	-0.004	0.008	0.006
	-0.008	-0.008		-0.005	-0.004		0.012	0.010
$\alpha_2 \approx$	49.597°	-0.000	$M_2 \approx$	0.584	0.001	$\omega \approx$	0.074	-0.002

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-1.095	0.000	0.113	8.443
area	-0.101	-1.099	-1.127	-0.008	14.337
mass flux	1.039	1.039	1.039	1.013	-1.880
VZLU	0.000	0.000	0.000	0.000	-0.000

Kobra: $\mathrm{M}_1 = 0.795$, $p_{01} \approx 0.980{\cdot}10^5$ Pa; $\alpha_1 = 59°$; z/H = 50 %

0.195	0.201	0.201	-0.001	-0.003	-0.003	-0.003	0.003	0.003
	0.006	0.006		-0.003	-0.002		0.006	0.005
$\alpha_2 \approx$	47.361°	0.000	$M_2 \approx$	0.530	0.000	$\omega \approx$	0.026	-0.001

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.701	0.000	0.060	10.918
area	-0.047	-0.681	-0.660	0.002	21.698
mass flux	0.647	0.647	0.647	0.638	-2.272
VZLU	0.000	0.000	0.000	0.000	-0.000

Kobra: $\mathrm{M}_1 = 0.806$, $p_{01} \approx 0.977{\cdot}10^5$ Pa; $\alpha_1 = 61°$; z/H = 50 %

0.154	0.157	0.157	-0.001	-0.003	-0.003	-0.002	0.003	0.002
	0.003	0.003		-0.002	-0.002		0.005	0.004
$\alpha_2 \approx$	47.620°	0.000	$M_2 \approx$	0.586	0.000	$\omega \approx$	0.026	-0.001

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.549	0.000	0.057	9.676
area	-0.036	-0.515	-0.505	0.008	18.486
mass flux	0.494	0.494	0.494	0.484	-2.764
VZLU	0.000	0.000	0.000	0.000	0.000

Kobra: $\mathrm{M}_1 = 0.807$, $p_{01} \approx 0.974{\cdot}10^5$ Pa; $\alpha_1 = 62°$; z/H = 50 %

0.193	0.197	0.197	-0.001	-0.003	-0.003	-0.002	0.003	0.002
	0.003	0.003		-0.003	-0.002		0.006	0.005
$\alpha_2 \approx$	46.777°	0.000	$M_2 \approx$	0.539	0.000	$\omega \approx$	0.029	-0.001

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.686	0.000	0.062	9.070
area	-0.042	-0.651	-0.639	0.008	18.046
mass flux	0.626	0.626	0.626	0.617	-1.997
VZLU	0.000	0.000	0.000	0.000	-0.000

Kobra: $\mathrm{M}_1 = 0.797$, $p_{01} \approx 0.978{\cdot}10^5$ Pa; $\alpha_1 = 63°$; z/H = 50 %

0.288	0.277	0.277	-0.001	-0.005	-0.005	-0.003	0.005	0.004
	-0.011	-0.011		-0.004	-0.004		0.009	0.007
$\alpha_2 \approx$	47.105°	0.000	$M_2 \approx$	0.546	0.001	$\omega \approx$	0.060	-0.001

	I_M	I_A	I_C	I_H	I_S
MM	0.000	-0.965	0.000	0.093	7.155
area	-0.060	-0.920	-0.958	0.014	13.054
mass flux	0.887	0.887	0.887	0.872	-1.127
VZLU	0.000	0.000	0.000	0.000	-0.000

Figure 3: Comparison of Data Reduction Methods on compressor Kobra testcase

TRW2: $p_{01} \approx 0.961{\cdot}10^5$ Pa; z/H = 50 %

0.019	0.020	0.020	0.000	-0.001	-0.000	-0.000	0.001	0.001
	0.001	0.001		-0.001	-0.000		0.002	0.001
$\alpha_2 \approx$	62.160°	0.000	$M_2 \approx$	0.628	0.000	$\xi \approx$	0.025	-0.000

I_M	I_A	I_C	I_H	I_S	
0.000	-0.085	0.000	0.008	3.458	MM
-0.010	-0.093	-0.091	-0.001	5.064	area
0.089	0.089	0.089	0.086	-1.386	mass flux
0.000	0.000	0.000	0.000	0.000	VZLU

TRW2: $p_{01} \approx 0.961{\cdot}10^5$ Pa; z/H = 50 %

0.087	0.128	0.128	-0.008	-0.002	-0.008	0.010	0.009	0.009
	0.042	0.042		0.006	0.000		-0.001	-0.001
$\alpha_2 \approx$	65.485°	0.000	$M_2 \approx$	1.108	-0.006	$\xi \approx$	0.032	-0.000

I_M	I_A	I_C	I_H	I_S	
0.000	-0.591	0.000	0.297	30.118	MM
1.008	1.292	1.487	1.003	-1.653	area
1.246	1.246	1.246	1.460	-0.502	mass flux
0.000	0.000	0.000	0.000	-0.000	VZLU

TRW2: $p_{01} \approx 0.961{\cdot}10^5$ Pa; z/H = 50 %

-1.407	-0.659	-0.659	-0.010	0.017	0.008	0.023	0.019	0.019
	0.747	0.747		0.027	0.019		-0.003	-0.003
$\alpha_2 \approx$	54.887°	0.000	$M_2 \approx$	1.563	-0.008	$\xi \approx$	0.040	0.000

I_M	I_A	I_C	I_H	I_S	
0.000	2.466	0.000	-0.356	59.256	MM
0.059	-0.663	2.142	-0.723	-7.481	area
3.240	3.240	3.240	3.599	2.281	mass flux
0.000	0.000	0.000	0.000	-0.000	VZLU

Figure 4: Comparison of Data Reduction Methods on turbine TRW2 testcase

SPLEEN: $p_{01} \approx 0.107{\cdot}10^5$ Pa; z/H = 50 %

0.024	0.034	0.034	-0.000	-0.001	-0.001	-0.000	0.001	0.001
	0.010	0.010		-0.001	-0.000		0.002	0.001
$\alpha_2 \approx$	53.092°	0.000	$M_2 \approx$	0.663	0.000	$\xi \approx$	0.037	-0.000

I_M	I_A	I_C	I_H	I_S	
0.000	-0.123	0.000	0.015	2.664	MM
-0.011	-0.123	-0.088	-0.001	3.567	area
0.118	0.118	0.118	0.113	-1.035	mass flux
0.000	-0.000	0.000	0.000	-0.000	VZLU

SPLEEN: $p_{01} \approx 0.105{\cdot}10^5$ Pa; z/H = 1 %

-0.095	0.355	0.355	-0.006	-0.006	-0.005	0.011	0.013	0.011
	0.450	0.450		-0.000	0.001		0.002	-0.000
$\alpha_2 \approx$	60.189°	0.000	$M_2 \approx$	0.581	0.001	$\xi \approx$	0.167	-0.002

I_M	I_A	I_C	I_H	I_S	
0.000	-1.426	0.000	0.111	5.898	MM
0.002	-1.385	0.427	-0.014	-0.045	area
1.461	1.461	1.461	1.443	0.200	mass flux
0.000	0.000	0.000	0.000	0.000	VZLU

SPLEEN: $p_{01} \approx 0.096{\cdot}10^5$ Pa; z/H = 50 %

0.026	0.059	0.059	-0.001	-0.002	-0.001	0.000	0.003	0.002
	0.032	0.032		-0.001	-0.000		0.002	0.002
$\alpha_2 \approx$	52.935°	0.000	$M_2 \approx$	0.841	0.001	$\xi \approx$	0.032	-0.001

I_M	I_A	I_C	I_H	I_S	
0.000	-0.213	0.000	0.038	5.407	MM
-0.028	-0.217	-0.099	-0.014	4.947	area
0.212	0.212	0.212	0.197	-2.613	mass flux
0.000	0.000	0.000	0.000	-0.000	VZLU

SPLEEN: $p_{01} \approx 0.180{\cdot}10^5$ Pa; z/H = 50 %

0.012	0.023	0.023	-0.000	-0.001	-0.000	-0.000	0.001	0.001
	0.011	0.011		-0.000	-0.000		0.001	0.001
$\alpha_2 \approx$	52.938°	0.000	$M_2 \approx$	0.758	0.000	$\xi \approx$	0.028	-0.000

I_M	I_A	I_C	I_H	I_S	
0.000	-0.084	0.000	0.013	3.053	MM
-0.015	-0.096	-0.055	-0.009	3.169	area
0.092	0.092	0.092	0.086	-1.539	mass flux
0.000	0.000	0.000	0.000	-0.000	VZLU

SPLEEN: $p_{01} \approx 0.169{\cdot}10^5$ Pa; z/H = 50 %

0.018	0.037	0.037	-0.000	-0.001	-0.001	0.000	0.002	0.001
	0.018	0.018		-0.001	-0.000		0.002	0.001
$\alpha_2 \approx$	52.903°	0.000	$M_2 \approx$	0.831	0.000	$\xi \approx$	0.029	-0.001

I_M	I_A	I_C	I_H	I_S	
0.000	-0.133	0.000	0.023	3.590	MM
-0.018	-0.136	-0.069	-0.008	3.557	area
0.131	0.131	0.131	0.121	-1.859	mass flux
0.000	0.000	0.000	0.000	-0.000	VZLU

Figure 5: Comparison of Data Reduction Methods on turbine SPLEEN testcase

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