Chapter 13
Automated Correlation of Simulations and Experiments for Digital Twin Development

G. Brunbauer, A. M. Puhwein, and M. J. Hochrainer

Abstract Accurate experimental validation of finite element models with 3D scanning laser Doppler vibrometry measurements is crucial for reliable structural-dynamics simulations, especially for large or complex systems. When entire test rigs are measured, experimental modal analysis of individual components is infeasible and the finite element model must inevitably include non-trivial boundary conditions. Although commercial software tools offer automated correlation algorithms, these often fail when applied to large models with point masses, rigid bodies, contacts or mismatched geometries. Therefore a transparent workflow is presented to validate complex numerical models using 3D vibrometry data. It covers import and processing of simulated and measured modal data, alignment of measurement grids and FE mesh, robust eigenvector interpolation and correlation via modal assurance criterion. Unlike black-box tools, the proposed open implementation allows full control of each step within the validation process. The workflow proposed has proven to work reliably on a large FE model of a twin-disc tribometer and builds a suitable basis for realistic digital twin modelling.

Keywords Digital Twin · Correlation · FEM · Modal Analysis · SLDV

Introduction

Modern high fidelity finite element (FE) models are of high practical value for the design and optimisation of mechanical structures. However this is restricted to models which behave similar to the real structure, thus simulation parameters must be matched with measurements. Correlating FE analysis with 3D scanning laser Doppler vibrometry (3D-SLDV) is an state of the art approach to tune and validate numerical models in order to predict the system dynamics [1].

Applications reach from aviation [1, 2] and aerospace [3, 4] to automotive [5] and mechanical engineering [6]. Correlating simulations and measurements is important in tribology, since direct measurements in the contact zone are rarely feasible [7]. Dedicated friction test rigs (tribometers) enable controlled experiments [8], but the influence of machine dynamics on experimental results often remains unknown [9]. Therefore, numerical models of tribometers are used to study contact forces and structural vibrations to improve tribometer design and test quality [10].

Modern FE tools allow the modelling of complex structures by integrating e.g. bolt pretension, nonlinear contacts, nonlinear joints, or rigid bodies [11]. Reduced modal models can be embedded in multi body simulations with application-dependent contact models to form digital twins [10].

However, validation of FE models against measurements is challenged by (i) spatial limitations due to line-of-sight constraints, (ii) limited frequency resolution due to relatively short acquisition times in point-by-point scanning, (iii) mismatched geometries and (iv) multiple datasets with rather weak excitations [1, 2, 3]. Furthermore, correlation of large numerical models can cause stability or runtime problems.

To address these issues, a flexible workflow for validating FE models with multiple 3D-SLDV datasets is introduced. It provides, consistent import and processing of simulation and measurement results, spatial transformation of datasets into the

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FE reference frame, efficient interpolation of aligned mode shapes, and correlation using modal assurance criterion (MAC) [12]. The open, well structured implementation enables transparency and control throughout validation.

The approach is demonstrated for a twin-disc tribometer, showing reliable model validation as a base for model tuning and realistic digital-twin development.

Correlation Workflow

Figure 1 illustrates the proposed workflow: First, the simulation and identification datasets j from varying perspectives i are matched (step a). After reducing the data for efficient computation, measurement data sets are transformed by aligning scan grid and FE mesh. Then, simulated eigenvectors are interpolated at the scan points and correlation is quantified via MAC (step b). The various MAC matrices are finally assembled and reduced via mode matching (step c), see Section for a detailed description.

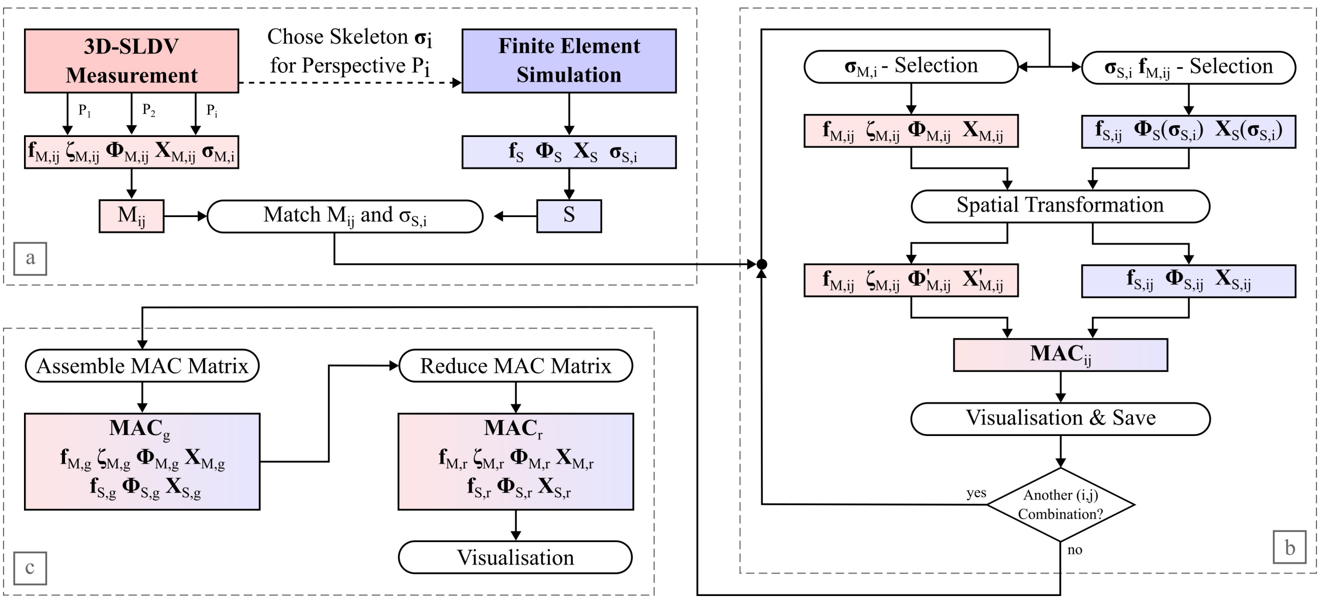

Fig. 1 Correlation workflow: a) load simulation S and measurement M_{ij} data, match FE node selection $\boldsymbol{\sigma}_{S,i}$ per perspective with M_{ij}, b) select frequency range ($\mathbf{f}_{M,ij}$ selection) and spacial distribution ($\boldsymbol{\sigma}_{M,i}$ and $\boldsymbol{\sigma}_{S,i}$ selection), transform M_{ij}, interpolate FE mode shapes to scan point coordinates, compute $\boldsymbol{MAC}_{ij}$ per combination and c) assemble/reduce results. $\mathbf{f}$ are natural frequencies, $\boldsymbol{\zeta}$ modal damping ratios, $\boldsymbol{\Phi}$ is the modal matrix, $\mathbf{X}$ the coordinate frame and $\boldsymbol{\sigma}$ a point-ID set.

Use Case: Twin-Disc Tribometer

The workflow is demonstrated for a large-scale FE model (~900 k DoF) of a twin-disc tribometer, see Figure 2 a), including nonlinear contacts, pretensioned bolts, nonlinear joints, springs and rigid bodies. The linear modal analysis of the nonlinear FE model contains 400 modes, rendering frequencies up to 2.8 kHz. The tribometer consists of two discs, mounted on independently driven shafts, pressed against each other with a defined force, see [13, 14] for details.

To capture the dynamics of the tribometer a 3D-SLDV measurement setup with triaxial accelerometer references is used. Impulse hammer measurements are captured for multiple components from five perspectives, see Figure 2 a). Furthermore, operational measurements are carried out with and without slippage between the discs [14].

The identification of modal parameters is based on stochastic subspace identification for both operational and experimental modal analysis [15].

Correlation Workflow

Regardless of the identification type, the data set

$$M_{ij} = \{\mathbf{f}_{M,ij},\, \boldsymbol{\zeta}_{M,ij},\, \boldsymbol{\Phi}_{M,ij},\, \mathbf{X}_{M,ij}\},$$

is stored for each perspective–identification pair (i, j). An optional user defined mask $\boldsymbol{\sigma}_{M,i}$, consisting of scan point-IDs, can also be used to reduce the size of each M_{ij}. Vector $\mathbf{f}$ contains natural frequencies, $\boldsymbol{\zeta}$ modal damping ratios, $\boldsymbol{\Phi}$ is the modal matrix and $\mathbf{X}$ the coordinate frame.

To export the modal simulation data

$$S = \{\mathbf{f}_S, \boldsymbol{\Phi}_S, \mathbf{X}_S\}$$

from the FE result file one can either use FE-tool scripting or extract the required information from the result file directly using e.g. an application programming interface [16]. For each scanning perspective i, FE node-ID sets $\boldsymbol{\sigma}_{S,i}$ are defined to restrict subsequent processing to the relevant geometry regions. Geometric features (surfaces, edges) can be used to define the regions of interest.

Prior to the spatial transformation of the measurement results (alignment of point clouds), the datasets M_{ij} and S are matched. Each M_{ij} is mapped to the corresponding $\boldsymbol{\sigma}_{S,i}$ based on a user-defined map. S is then reduced for each M_{ij} to the $\boldsymbol{\sigma}_{S,i}$ node-IDs and to the frequency range of interest (pass band $\mathbf{f}_{M,ij}$), yielding the reduced simulation data $\mathbf{f}_{S,ij}$, $\boldsymbol{\Phi}_S(\boldsymbol{\sigma}_{S,i})$ and $\mathbf{X}_S(\boldsymbol{\sigma}_{S,i})$.

To determine the used point cloud alignment the least squares problem

$$L_i = \sum_k \left\|\mathbf{x}_{S,k} - \left(\mathbf{R}_i\,\mathbf{x}_{M,k} + \mathbf{t}_i\right)\right\|^2 \rightarrow min,$$

is solved for every perspective i for k manually selected reference points $\mathbf{x}_{S,k}$ and $\mathbf{x}_{M,k}$, rendering the rotation matrix $\mathbf{R}_i$ as well as the transformation vector $\mathbf{t}_i$. M_{ij} is aligned to S by the rigid transform

$$\boldsymbol{\Phi}'_{M,ij} = \mathbf{R}_i\,\boldsymbol{\Phi}_{M,ij}, \qquad \mathbf{X}'_{M,ij} = \mathbf{R}_i\,\mathbf{X}_{M,ij} + \mathbf{t}_i.$$

To minimise computational costs and inaccurate extrapolation, FE nodes without corresponding measurement points are removed yielding the reduced modal matrix $\boldsymbol{\Phi}_{S,ij}$ and coordinates $\mathbf{X}_{S,ij}$, see Figure 2 b).

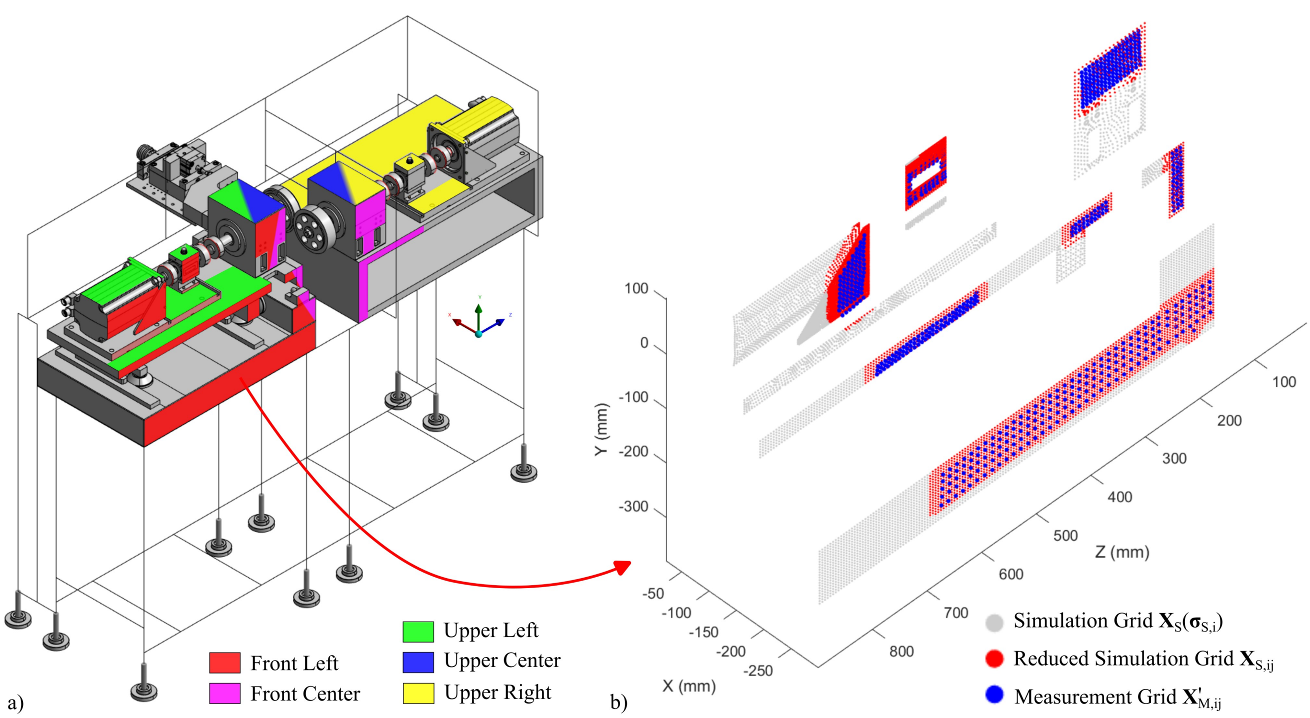

Fig. 2 a) FE model of the twin-disc tribometer with highlighted scanning perspectives, $\boldsymbol{\sigma}_{S,i}$ respectively. b) Exemplary transformation result for the perspective *Front Left*: The measurement grid $\mathbf{X}'_{M,ij}$ is already transformed to the simulation mesh $\mathbf{X}_S(\boldsymbol{\sigma}_{S,i})$ yielding the reduced coordinates $\mathbf{X}_{S,ij}$ for a distance threshold of 20 mm.

Because the FE nodes and measurement points do not coincide, the FE results $\boldsymbol{\Phi}_{S,ij}$ are interpolated at the transformed measurement points $\mathbf{X}'_{M,ij}$ yielding the interpolated modal matrix $\tilde{\mathbf{\Phi}}_{S,ij}$. For each identification dataset the

$$\mathbf{MAC}_{ij} = \frac{\left| (\mathbf{\Phi}'_{M,ij})^\top \tilde{\mathbf{\Phi}}_{S,ij} \right|^2}{\left((\mathbf{\Phi}'_{M,ij})^\top \mathbf{\Phi}'_{M,ij}\right) \left(\tilde{\mathbf{\Phi}}_{S,ij}^\top \tilde{\mathbf{\Phi}}_{S,ij}\right)},$$

is computed. Node ID selection (spatial reduction) and frequency-band selection (frequency reduction), decrease processing requirements substantially.

All $\boldsymbol{MAC}_{ij}$ are assembled to a global matrix $\mathbf{MAC}_g$, by clustering the subsets and thereby eliminating the different perspectives. Then, the reduced matrix $\mathbf{MAC}_r$ is obtained from $\mathbf{MAC}_g$ in a three step procedure. First, the size is reduced by neglecting mode pairs whose MAC is below a predefined threshold value τ. Next, combinations with a relative natural frequency deviation of

$$\frac{|f_M - f_S|}{f_S} \leq \delta,$$

are selected as valid matches where δ defines the frequency corridor. Finally, a square matrix is obtained by keeping unique mode pairs, based on the maximum MAC values, while ensuring each simulated and each measured mode is used only once.

Results and Discussion

Figure 3 a) shows the valid matches for the twin-disc tribometer within a frequency corridor of $\delta = 0.3$ and a value $MAC \geq 0.7$ up to 500 Hz. The figure clearly illustrates whether modes with high correlation cluster along the main diagonal or deviate significantly in frequency. In the study 38 unique mode pairs can be selected within the valid matches and are further investigated. Figure 3 b) shows the selected mode pairs of $\mathbf{MAC}_r$ in matrix form. Two exemplary images of the

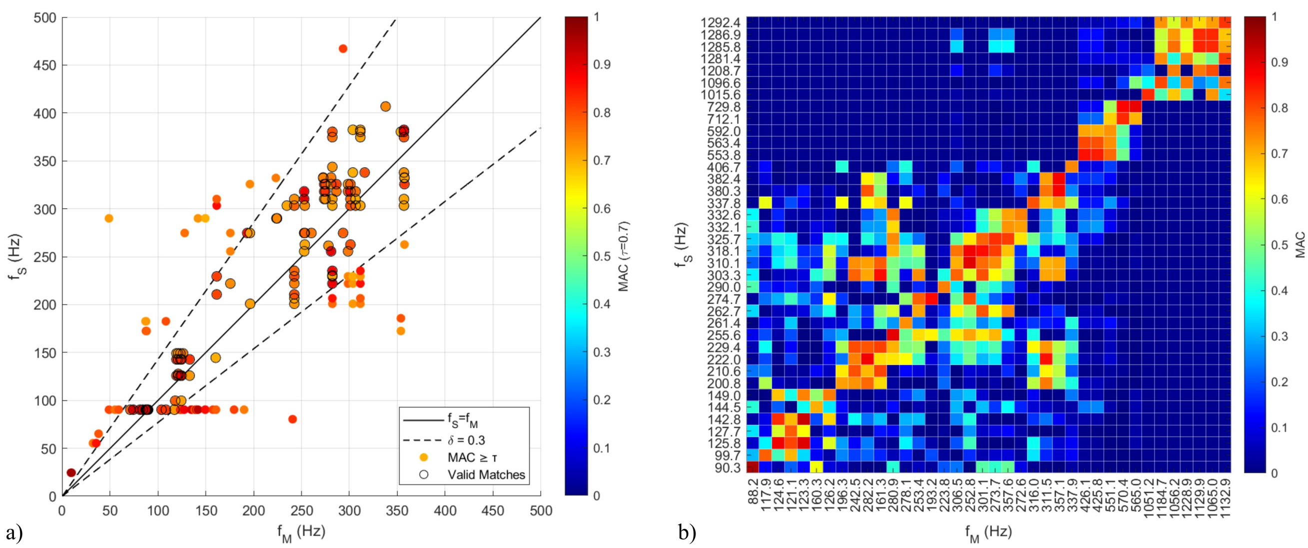

Fig. 3 Results for twin-disc tribometer for $\delta = 0.3$ and $\tau = 0.7$ a) Mode pairs with $MAC \geq 0.7$ and valid mode matches within δ corridor b) Reduced matrix $\mathbf{MAC}_r$ for unique mode pairs within valid matches.

mode animation with normalised and scaled amplitudes is given in Figure 4, where good qualitative agreements of the mode shapes can be observed.

The results show, that the proposed workflow robustly recovers mode pairs across five perspectives and different identification data sets. The entire computation, including data loading and user inputs, only takes a few minutes. Main practical limitations arise from incomplete scan coverage, high local mode density, noisy measurement data and varying reference sensors, preventing combined identification. These limitations can be further mitigated by using the FE model to focus on measurement coverage in frequency ranges and geometry areas with high mode density and by increasing measurement duration per scan point. The reduced set $\mathbf{MAC}_r$ provides compact input for visualisation and targeted model updating.

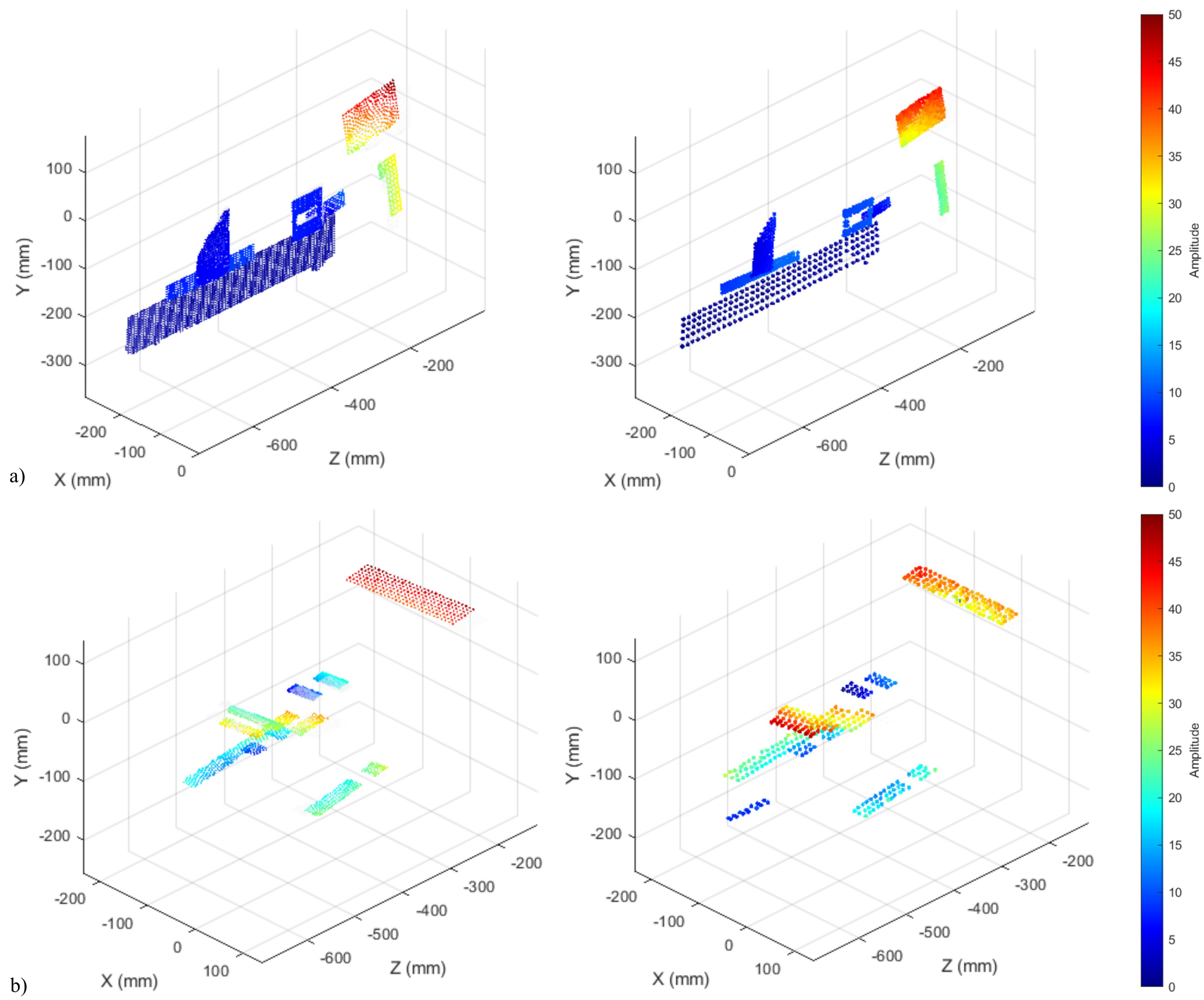

Fig. 4 Exemplary normalised visualisation of matched mode pairs between simulation (left) and measurement (right), scale factor 50
a) Perspective *Front Left*, $MAC = 0.96$, $f_S = 90.30\,Hz$, $f_M = 80.15\,Hz$, $\delta = -2.38\%$
b) Perspective *Upper Left*, $MAC = 0.89$, $f_S = 125.80\,Hz$, $f_M = 124.56\,Hz$, $\delta = -0.98\%$

Conclusion

A workflow for validating complex FE models with 3D-SLDV data is presented, which processes simulation and identification results, aligns mismatched coordinate frames, interpolates FE mode shapes to the scan grids and quantifies correlation via MAC. User input is kept to a minimum and is mainly required for coordinate transformation. On a large FE model of a twin-disc tribometer the workflow proved robust and practical, enabling reliable model validation and a compact one-to-one set of matched modes for visual inspection and further analysis. The correlation strongly depends on the measurement quality and the spatial scan coverage. For large structures with high modal density and localised modes, sparse scan coverage, or regions with line-of-sight restrictions, the correlation quality may be limited, resulting in non-diagonal matches or gaps in the assembled MAC matrix.

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