

TenSyGrid

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1 Tensor Notation

A tensor is an N-way array where its values are accessed by N indices. In this sense, a vector is an order 1 tensor and a matrix an order 2 tensor. A tensor of order n in the real numbers can be defined as $F \in \mathbb{R}^{I_1 \times \dots \times I_n}$, where I_i is the dimension of the i_{th} order.

Let F be a tensor in $F \in \mathbb{R}^{\times 2^n}$ of order n , where each dimension has length 2.

1.1 Tensor Operations

Tensor Product

Let $F \in \mathbb{R}^{j_1 \times \dots \times j_m}$ and $G \in \mathbb{R}^{i_1 \times \dots \times i_n}$. Then the tensor product $F \otimes G \in \mathbb{R}^{j_1 \times \dots \times j_m, i_1 \times \dots \times i_n}$ has the entries for $\forall a_k \in \{1, \dots, j_k\}, b_k \in \{1, \dots, i_k\}$:

$$(F \otimes G)_{a_1, \dots, a_m, b_1, \dots, b_n} := f_{a_1, \dots, a_m} \cdot g_{b_1, \dots, b_n} \quad (1)$$

Inner Product

The inner product of two tensors of same order and dimension $F, G \in \mathbb{R}^{j_1 \times \dots \times j_m}$ is a scalar that has the same properties of a vector product and is defined as:

$$\langle F, G \rangle = \sum_{d_1=1}^{j_1} \sum_{d_2=1}^{j_2} \dots \sum_{d_n=1}^{j_n} a_{d_1 d_2 \dots d_n} b_{d_1 d_2 \dots d_n} \quad (2)$$

This concept can be generalized for tensors of different dimensions. In this case the inner product can be interpreted as a form of order contraction.

Monomial Tensor

Let $x \in \mathbb{R}^n$ a vector. Then $m(x) \in \mathbb{R}^{2^n}$ is a vector such that each entry is a unique multilinear monomial of coefficient 1. More specifically, $m(x)$ is defined as follows:

$$m(x) := \begin{pmatrix} 1 \\ x_1 \end{pmatrix} \otimes \dots \otimes \begin{pmatrix} 1 \\ x_n \end{pmatrix} \quad (3)$$

Let $x \in \mathbb{R}^n$ a vector. We define $M(x) \in \mathbb{R}^{\times 2^n}$ as the monomial tensor that is defined as follows. We can see that $M(x)$ is a reshaping of the monomial vector $m(x)$, $a_i \in \{0, 1\} \forall i$.

$$(M(x))_{a_1, \dots, a_n} := \prod_{i=1}^n x_i^{a_i} \quad (4)$$

1.2 Properties

Let $F \in \mathbb{R}^{\times 2^n \times p}$ be a tensor of order $n + 1$. And $\forall i \in \{0, \dots, n\}$ there exist $F_{x_i} \in \mathbb{R}^{2 \times r}$ and $F_\phi \in \mathbb{R}^{p \times r}$ such that, where $F_i(k)$ is the k_{th} column of F_{x_i} .

$$F = \sum_{k=0}^r F_{x_1}(k) \otimes \dots \otimes F_{x_n}(k) \otimes F_\phi(k) \quad (5)$$

Then we say that $[F_{x_1}, \dots, F_{x_n}, F_\phi]$ is a decomposition of rank r of F . Additionally, if we consider a vector $x \in \mathbb{R}^n$ we have that the following equation holds true:

$$\langle F, M(x) \rangle = F_\phi(F_{x_1}^T \begin{pmatrix} 1 \\ x_1 \end{pmatrix} \otimes \dots \otimes F_{x_n}^T \begin{pmatrix} 1 \\ x_n \end{pmatrix}) \quad (6)$$

2 Multilinear models

A multi linear equation takes the form of:

$$p(x) = \sum_{i_n=0}^{i_n=1} \dots \sum_{i_1=0}^{i_1=1} a_{i_1, \dots, i_n} x_1^{i_1} \dots x_n^{i_n} \quad (7)$$

$$(8)$$

We can establish a relationship between the coefficients of a multilinear polynomial in $x \in \mathbb{R}^n$ and the entries of a tensor $F \in \mathbb{R}^{\times 2^n}$. The following equation describes the relationship between the multi linear polynomial $p(x)$ and a tensor F .

$$F_{i_1, \dots, i_n} = a_{i_1, \dots, i_n} \quad (9)$$

2.1 Multilinear Time Independent Models

Multilinear Time Independent models or (MTI) describes a system and its evolution over time. The values used to define the system's operations are the following:

- $x \in \mathbb{R}^n$ the state.
- $y \in \mathbb{R}^p$ the output.

- $u \in \mathbb{R}^m$ the input.

Additionally, we need to consider the system's equations. Using the previous tensor notation we can describe the system equations explicitly as follows, where $F \in \mathbb{R}^{\times_2(n+m) \times n}$, $G \in \mathbb{R}^{\times_2(n+m) \times p}$:

$$\dot{x} = \langle F | M(x, u) \rangle \quad (10)$$

$$y = \langle G | M(x, u) \rangle \quad (11)$$

Another way to define an MTI's evolution is through the use of an implicit multilinear (iMTI) equation. In this case the tensor $H \in \mathbb{R}^{\times_2(2n+m+p) \times n+p}$ defines the state evolution. Additionnally, we would need to add the conditions $\det(\partial_{\dot{x}} H) \neq 0$, $\det(\partial_y H) \neq 0$ for the system to be properly defined (implicit function theorem). Otherwise, more equations would be needed to define the system completely.

$$\langle H | M(\dot{x}, x, u, y) \rangle = 0 \quad (12)$$

It is clear that the explicit formulation can be transformed into the implicit one such that the resulting system is: Where \bar{H} is chosen appropriately to represent the $(n + p)$ multilinear equations $\dot{x} - \langle F | M(x, u) \rangle = 0$ and $y - \langle G | M(x, u) \rangle = 0$.

$$\langle \bar{H} | M(\dot{x}, x, u, y) \rangle = 0 \quad (13)$$

2.2 Differential Algebraic Equations

Differential Algebraic Equations (DAE) are a set of problems defined by differential equations and another set of algebraic equations. An explicit formulation of a DAE can be done as follows: Where $x \in C(\mathbb{R}^n, \mathbb{R})$, $y \in C(\mathbb{R}^n, \mathbb{R})$, $t \in \mathbb{R}$

$$\dot{x} = f(x, z, t) \quad (14)$$

$$0 = g(x, z, t) \quad (15)$$

It is clear from the previous equation that ODEs are a special case of DAEs where $g(x, z, t) = 0$. In general, DAEs are tightly linked with ODEs. One way to link them together is through the concept of index. The (differential) index of a DAE is the number of times the equations of the DAE need to be differentiated in order to recover an explicit ODE. However, it is important to note that the index is dependent on the formulation of the DAE as well as on the solution provided. Usually, a higher index means the DAE involves more complexity specially when solving it numerically.

The explicit form of a DAE is specifically useful since it enables To solve numerically the problem in a straightforward manner. First, considering the implicit function $aux(x, t)$ that yields a set of variables z such that $g(x, aux(x, t), t) = 0$. And then substituting in the first equation. In pseudo-code this yields:

Algorithm 1 Implicit Stepforward

```
1: Initialize  $x_0 \in X$  initial state.  
2: Initialize  $z_0 \in Z$  initial auxiliary variables.  
3: for  $t = 0$  to  $T$  do  
4:   Define  $aux(x, t)$   
5:   Solve  $f(x_{t+1}, aux(x_{t+1}, t+1), t+1) = 0$  for variable  $x_{t+1}$ .  
6:    $x_{t+1} \leftarrow x^*$   
7: end for
```

However this method does not always yield good numerical results. For this purpose, we will explore different numerical methods and analyse how they compare to each other and, more specifically, which one fits the type of DAE that we are studying best.

3 Numerical Methods

3.1 Numerical Methods for ODE's

ODEs can be represented by the following implicit equation:

$$f(x, \dot{x}, t) = 0 \quad (16)$$

One specific method to solve a system of ODE are implicit methods. This is a type of family of methods that discretizes the time variable into a set of timesteps $\mathcal{T} := \{1, \dots, T\}$. An initial value x_0 for x is given and then the following values are found by solving an equation involving the function in ???. More specifically, we solve the equation $g(x_{t+1}, x_t) = 0$ where x_t is known, x_{t+1} is the unknown, and g has the following expression:

$$g(x_{t+1}, x_t) = f(x_{t+1}, \frac{x_{t+1} - x_t}{\Delta t}, t+1) \quad (17)$$

This method consists of solving iteratively an implicit system of equations. These type of systems are usually solved using Newton-Raphson methods. These methods demand a fixed number of evaluations of the function to be solved.

We want to adapt this method to solve an explicit DAE as in ??. To do so we define a new function $\bar{F}(x, u)$ that can be used as the implicit function.

$$\bar{F}(\dot{x}, x, z, u) = \begin{pmatrix} \dot{x} - < F | M(x, z, u) > \\ < G | M(x, z, u) > \end{pmatrix} \quad (18)$$

$$\bar{G}(x_{t+1}, x_t, z_{t+1}, u_{t+1}) = \bar{F}(\frac{x_{t+1} - x_t}{\Delta t}, x_t, z_{t+1}, u_{t+1}) \quad (19)$$

We can describe the method in algorithmic form as follows:

Algorithm 2 Implicit Stepforward

```
1: Initialize  $x_0 \in X$  initial state.
2: Initialize  $z_0 \in Z$  initial auxiliary variables.
3: for  $t = 0$  to  $T$  do
4:   Solve for  $x_{t+1}, z_{t+1}, \bar{G}(x_{t+1}, x_t, z_{t+1}, u_{t+1}) = 0$ 
5:    $x_{t+1} \leftarrow x^*$ 
6:    $z_{t+1} \leftarrow z^*$ 
7: end for
```

4 Case Study 1

For this case study we define a non linear EDO of the following form: Where $x \in \mathcal{C}(\mathbb{R}^n, \mathbb{R})$, $A, B, C \in \mathbb{R}^{n \times n}$.

$$\dot{x}(t) = Ax(t) + B(x(t) \odot x(t)) + x^T(t)Cx(t) \quad (20)$$

The equation represents an EDO with a linear component A and a quadratic component B . The objective is to transform this ODE into a multi linear DAE. For this purpose, we add n auxiliary variables in the form of the vector v as well as n algebraic equations.

$$B(x(t) \odot x(t)) \quad (21)$$

$$\Leftrightarrow \begin{cases} B(u(t) \odot x(t)) \\ u(t) = x(t) \end{cases} \quad (22)$$

This yields the following multi linear DAE system:

$$\dot{x}(t) = Ax(t) + B(u(t) \odot x(t)) \quad (23)$$

$$0 = u(t) - x(t) \quad (24)$$

$$A = \begin{pmatrix} -0.5 & 0.1 & 0 & 0 & 0 \\ 0.5 & -0.2 & 0.1 & 0 & 0 \\ 0 & 0 & -0.3 & 0 & 0 \\ 0 & 0 & 0 & 0.4 & -0.1 \\ 0 & 0 & 0 & 0 & -0.2 \end{pmatrix},$$

$$B = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.1 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix},$$

$$C = \begin{pmatrix} 0 & 0.05 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.1 \end{pmatrix} \quad (25)$$

Finally we transform into the tensorized formulation of an iMTI. Where $F, G \in \mathbb{R}^{\times_2 2n \times n}$

$$\dot{x}(t) = \langle F | M(x, u) \rangle \quad (26)$$

$$0 = \langle G | M(x, u) \rangle \quad (27)$$

$$F_{i_1, \dots, i_n, j_1, \dots, j_n, k} = \begin{cases} A_{k,l} & \text{if } i_l = 1 \text{ and } \sum_{m=1}^n i_m + j_m = 1 \\ B_{k,l} + & \text{if } i_l = 1, j_l = 1 \text{ and } \sum_{m=1}^n i_m + j_m = 2 \\ 0 & \text{otherwise} \end{cases} \quad (28)$$

$$G_{i_1, \dots, i_n, j_1, \dots, j_n, k} = \begin{cases} 1 & \text{if } i_l = 1, l = k \text{ and } \sum_{m=1}^2 i_m + j_m = 1 \\ -1 & \text{if } j_l = 1, l = k \text{ and } \sum_{m=1}^2 i_m + j_m = 1 \\ 0 & \text{otherwise} \end{cases} \quad (29)$$

$$(30)$$

5 Case Study 2

For this case study we define a non linear EDO of the following form: Where $x \in \mathcal{C}(\mathbb{R}^n, \mathbb{R})$, $A_i \in \mathbb{R}^{n \times n} \quad \forall i$.

$$\dot{x}_i(t) = x^T(t) A_i x(t) \quad \forall i \in \{1, \dots, n\} \quad (31)$$

Using the same procedure done in the first case study we build the explicit multilinear tensor equations defining the model.

$$\dot{x}(t) = \langle F | M(x, u) \rangle \quad (32)$$

$$0 = \langle G | M(x, u) \rangle \quad (33)$$

$$F_{i_1, \dots, i_n, j_1, \dots, j_n, k} = \begin{cases} A_{k,l,m} + A_{k,m,l} & \text{if } l \neq m, \quad i_l = 1, i_m = 1 \text{ and } \sum_{m=1}^n i_m + j_m = 2 \\ A_{k,l,l} & \text{if } i_l = 1, j_l = 1 \text{ and } \sum_{m=1}^n i_m + j_m = 2 \\ 0 & \text{otherwise} \end{cases} \quad (34)$$

$$G_{i_1, \dots, i_n, j_1, \dots, j_n, k} = \begin{cases} 1 & \text{if } i_l = 1, l = k \text{ and } \sum_{m=1}^n i_m + j_m = 1 \\ -1 & \text{if } j_l = 1, l = k \text{ and } \sum_{m=1}^n i_m + j_m = 1 \\ 0 & \text{otherwise} \end{cases} \quad (35)$$

$$(36)$$

Let's us now analyze the DAE's index. By virtue of the equations being in explicit form the first equation are already a ODE so they are of differential index 0. On the other hand the algebraic equations consist exclusively of equations of the form $u_i = x_i$, therefore differentiating the n equations once already gives a EDO. This means that the DAE in this form is of index 1.