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Modelling and Validation of Joint Properties for NVH Simulation Model of an Electrified Passenger Vehicle Drivetrain

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Abstract – *The constantly changing automotive market, which is characterized by the progressing electrification of vehicles, presents challenges with respect to the acoustic behaviour of powertrains. As indicated frequently, the characteristic noise of electric cars differs from that of conventional drives. In particular, energy dissipation of the assembled housing parts from material and joint damping; is an important aspect. In modelling the NVH behavior of electric vehicles or drivetrains in general, the breakdown of global material and local joint damping is not yet state of the art. Instead, measured global modal damping values from similar constructions are frequently used. Often, a constant degree of damping is defined for all modes. However, moderate changes in the geometry of components or in the load level can lead to severe fluctuations in the damping. In order to improve predictability and to be able to estimate the effects of constructive changes in natural frequency, mode shape, and damping, the goal will be to take into account the global material and local joint damping separately. For that, a local model which is able to take the joint properties into account has to be developed. The analytical based Iwan model for the contact interface was expanded upon to facilitate model updating against forced response measurements on a simple mass spring structure in one dimension and to extend the model from one-dimensional to three-dimensional.*

Keywords: Micro-slip, macro-slip, tangential direction, lap-joint, Iwan model

1.0 INTRODUCTION

The acoustical properties of electrical vehicles have become an important concern for automobile manufacturers in recent years. The drivetrain in electric vehicles consists of shafts, bearings, fasteners and the housing. The electrical drivetrain technology department often studies the system behaviour of complete drivetrain and also the individual components on application of certain specific loads. To date, the research focus in this field has been to analyse complex, coupled and dynamic system behaviour of mechanical joints.

The cross-domain simulation chain presented in Figure 1 uses a force excitation model to show the structural-dynamic propagation of powertrain containing the electrical machine, gearbox and side shafts of the car. The airborne and structure-borne sound combines to form audible ear signal. The modular structure of the tool chain allows developers to change individual properties of the modelled drive components to quickly asses the resulting auralised car cabin noise.

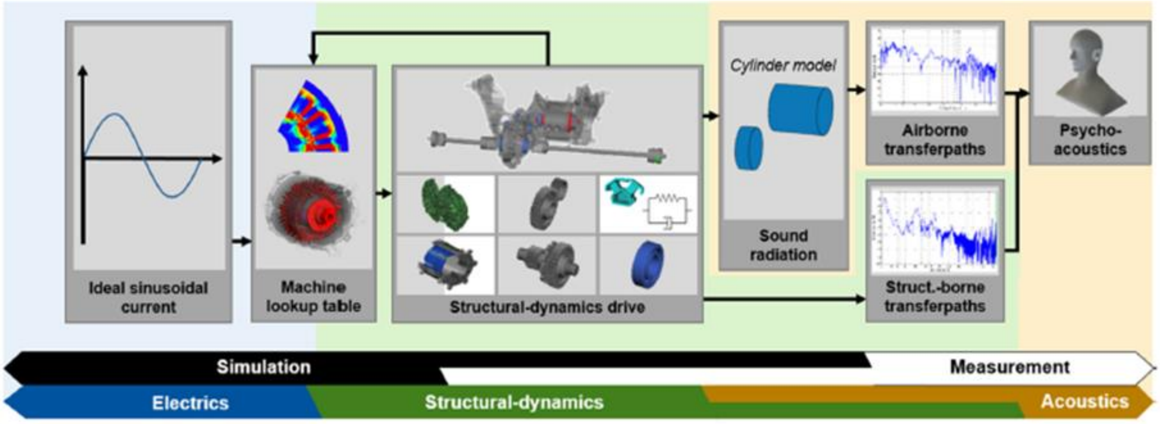

Figure 1: Schematic representation of the initial cross domain tool chain and its sub models (Müller-Giebeler et al., 2018)

2.0 PHYSICS OF CONTACT

This study is established on a lap-joint, which has two different structures of a common interface, with both components being held together with the help of a bolted connection (Figure 2). In general, lap joints are designed in such a way that the compressive load is sufficiently high to prevent the bulk relative motion of the two components (i.e. macro-slip). The movement along the interface between the two components is generally isolated and not complete throughout. This isolated movement is termed as Micro-Slip and precisely refers to the relative motion between the two interfaces that only occurs over part of the interface while the rest of the interface shows no relative motion. As the magnitude of the excitation is increased, the region of the micro-slip will increase until the entire interface shows relative (sliding) motion, which is macro-slip.

In designing lap-joint, the primary function is to connect stiffly two components. The active area of research, and thus the challenge, is associated with the secondary functions of the joint: the dissipative behaviour and the associated non-linearity, which have significant ramifications for structural dynamics. As a joint is exercised (either through the unavoidable micro-slip or the less frequent macro-slip), energy is dissipated through frictional processes that are not well understood. There are many factors that influence the energy dissipation, surface roughness, geometry, pre-load, materials, and the form of the stress waves propagating through the surface etc. (Brake, 2018).

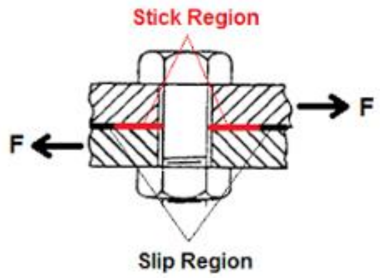

Figure 1: Stick and Slip region at the interface (Starr et al., 2013)

2.1 Tangential Behaviour

For the force-deformation relation in the tangential direction, however, the paths of successive cyclic re-loading and un-loading are different. In other words, the behaviour of a friction joint in the tangential direction is more of non-linearity (Figure 3). This indicates that energy is dissipated when the joint is subjected to a cyclic load. This loop (energy dissipation) does not exist under loading in the normal direction. The distinctive characteristic that the loop is effectively symmetrical with respect to the centre point of the loop. Therefore, it is possible to represent the re-loading and un-loading in some mathematical formulae. Because energy dissipation (and also effective non-linearity) does not exist under cyclic loading in a normal direction, it will not be investigated further in this study. Here, we shall deal with the properties of the joint in the tangential direction only.

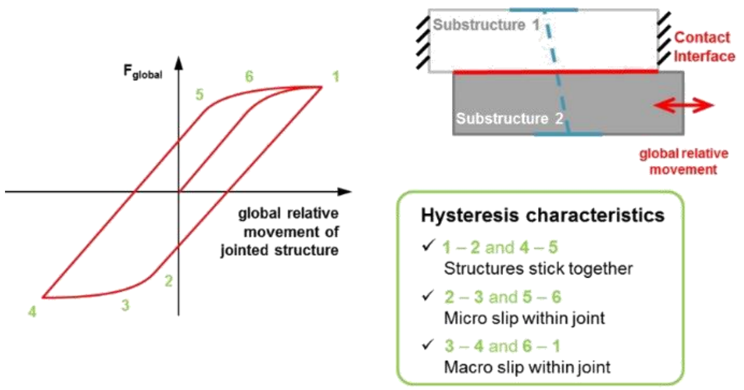

Figure 2: Behaviour of applied force to relative displacement in tangential direction (Magna, n.d.)

2.2 Normal Behaviour

In practice, a certain level of pre-load will be applied in the normal direction, and when the joint is subjected to a cyclic load in the normal direction, the joint will deform. Because the magnitude of the cyclic load is usually much smaller than that of the pre-load, the joint is more likely to deform. Since the force deformation relation is effectively linear, the behaviour of a friction joint in the normal direction is substantially linear (Thirukumaran & Indraratna, 2016).

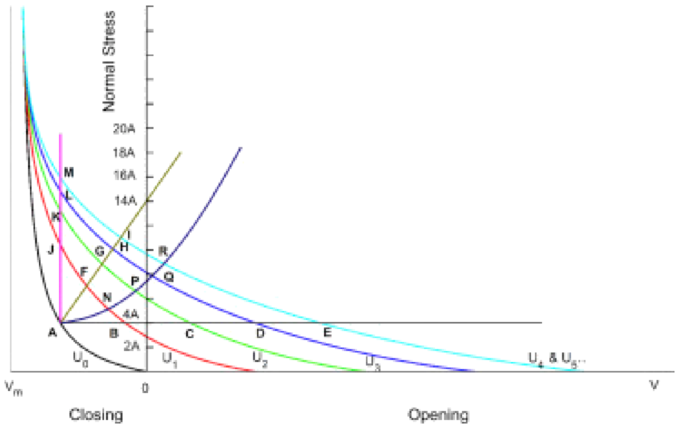

Figure 3: Normal stress versus normal displacement at different shear displacement (Thirukumaran & Indraratna, 2016)

2.3 Iwan 4-Parameter Model

Many calibrated models have been proposed to represent the stiffness and energy dissipation characteristics of a bolted joint. High Fidelity model is one of them, and it is a detailed finite element model with contact and friction. This requires quality mesh, high computing power and is more time consuming. Discrete models proposed by Iwan (1966) are also used for modelling of jointed structures. This requires the discretization of parameters that takes longer than the analytical representation of Iwan model as presented by Brake (2016).

A framework that has potential for providing that balance is due to Iwan (Segalman, 2005). One of his models, the most prominent, has been the parallel system of Jenkins elements, sometimes called the parallel series Iwan model as shown in Figure 5. Such a model consists of spring-slider units arranged in a parallel system. The four parameters defined by Iwan are as follows:

- F_S: Force necessary to cause macro-slip
- K_T: Joint stiffness under small applied load
- ϰ: Dissipation parameter at every instant
- β: Dissipation parameter for the complete curve of Force vs. Dissipation

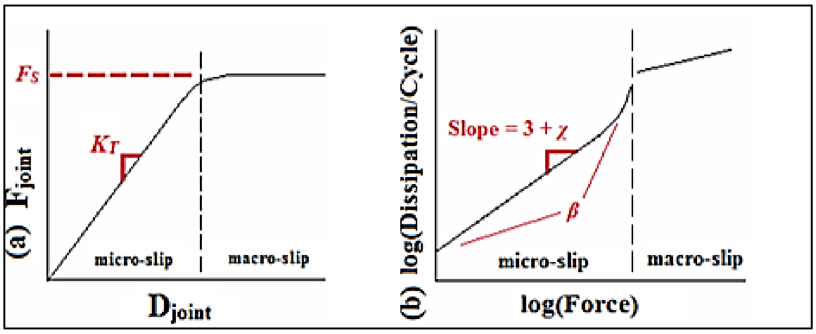

Figure 4: Representation of response of Micro-slip and Macro-Slip (Starr et al., 2013)

As a starting point, the four parameter Iwan model developed in Brake (2016):

$$F_{iwan} = \int \rho\,(\Phi)(u(t) - x(y, \Phi))d\Phi \quad (1)$$

$$u - x(t,\Phi) = \begin{cases} u, \; u < \Phi \; (if\ slider\ \Phi\ is\ stuck) \\ \Phi, \; u \geq \Phi \; (if\ slider\ \Phi\ is\ sliding) \end{cases} \quad (2)$$

The above equation describes a distribution ρ (Φ) of dry friction sliders (Jenkins elements) as shown in Figure 5. Note that in Segalman (2005), the global displacement U is used in place of the relative displacement u; in what follows, the relative displacement u is defined to be positive in the slip direction. The four parameter Iwan model of Segalman (2005) is subject to two Masing conditions which are both visible in Brake (2016). The forward and backward curves are reflective of one another and are scaled to fit between the initial loading point and the force for macro-slip. The displacement in the negative direction is the same as a displacement in the positive direction with the change in coordinates.

2.4 Brake's Function

The full expression of Iwan forces is given by Brake (2016). Additionally, δ_0 is defined to be the global displacement of the system at the start of a slip event, and F_O is defined to be the force due to the Iwan element at the start of a slip event. There are two cases that must be considered for cyclic loading; namely loading to micro-slip, and loading within the micro-slip regime. In loading to micro-slip, all of the Jenkins sliders are, by definition, in slip. For the first cycle of loading, it is assumed that $F_O = 0$ and $\delta_0 = 0$. After the first cycle, when the joint is macro-slip, $F_O = F_S$ and each Jenkins element is fully stretched in the direction opposite from the new loading direction.

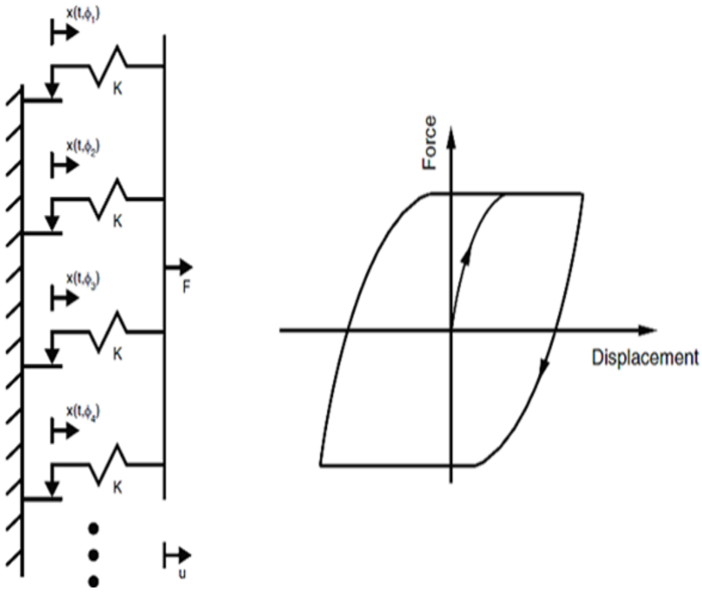

Figure 5: (Left): Drawing of an Iwan model as a parallel arrangement of dry friction sliders (Brake, 2016), (Right): Drawing of a typical hysteresis curve for a four parameter Iwan model described by (Brake, 2016)

$$F_{iwan} = \frac{Fs\,(x+1)}{\phi max^{x+2}\left(\beta+\frac{x+1}{x+2}\right)}\left(\left(\frac{1}{x+2}-\frac{1}{x+1}\right)u^{x+2}+\frac{\phi max^{x+1}}{x+1}u\right)+\frac{Fs}{\phi max}\frac{\beta}{\beta+\frac{x+1}{x+2}}\Gamma(u,\phi_{max}) \quad (3)$$

For oscillations between two extremes $-F_S$ and F_S, the equations are (Brake, 2016):

$$F_{loading} = \begin{cases} Fo + \frac{Fs-Fo}{Fs} Fiwan\left(u\frac{Fs}{Fs-Fo}\right) loading \\ Fo - \frac{-Fs-Fo}{-Fs} Fiwan\left(-u\frac{-Fs}{-Fs-Fo}\right) reverse\ loading \end{cases} \quad (4)$$

3.0 MATLAB MODEL

The formulation of this model is based on Iwan model. The Joint function is defined with the arguments as the displacement and velocity across the joint, as well as a structure containing the joint parameters.

3.1 Model Setup

As the response for the loading and reverse loading of forces is desired to complete the hysteresis curve, the sinusoidal wave with positive and negative values has been used as the initial excitation. The initialization of the model is done by declaring and initializing the input parameters and the variables required. The Brake's Function in Equation 3 and Equation 4 is used to calculate the hysteresis response.

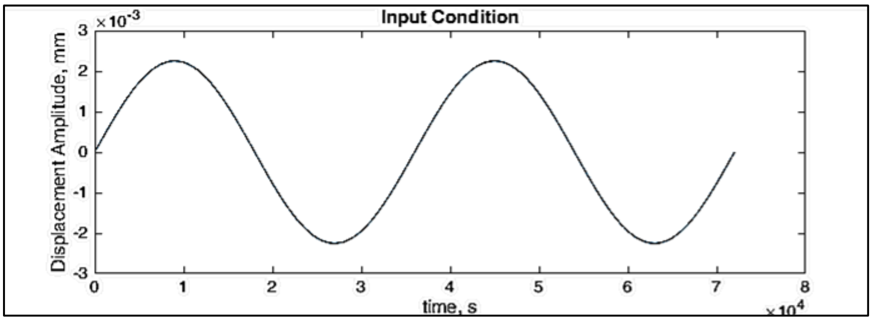

Figure 6: Input Function used for MATLAB

The parameters are chosen based on a 304 Stainless Steel lap joint. That is the common standard for stainless steel due to its malleability, high corrosive resistance and weldability.

Table 1: The list of parameters used to calculate Iwan model in MATLAB

Property	Symbol	Value
Tangential Stiffness	K_T	$1.5x10^7$N/m
Macro-Slip Force	F_S	4kN
Dissipation Exponent	$\varkappa$	-0.5
Stiffness Ratio	β	0.005
Maximum displacement	ϕ_{max}	$7.9x10^{-4}$

The process is then repeated for 72001 times. The velocity is used to detect a change in loading and unloading, and is calculated by the difference of the new value and the previous values of the displacement in every iteration. As the complete hysteresis curve is made up of three cycles and at the beginning of every cycle, the initial conditions (F_O = do = 0) are defined, and the values of local force and local displacement are updated to global force and global displacement at the end of every cycle.

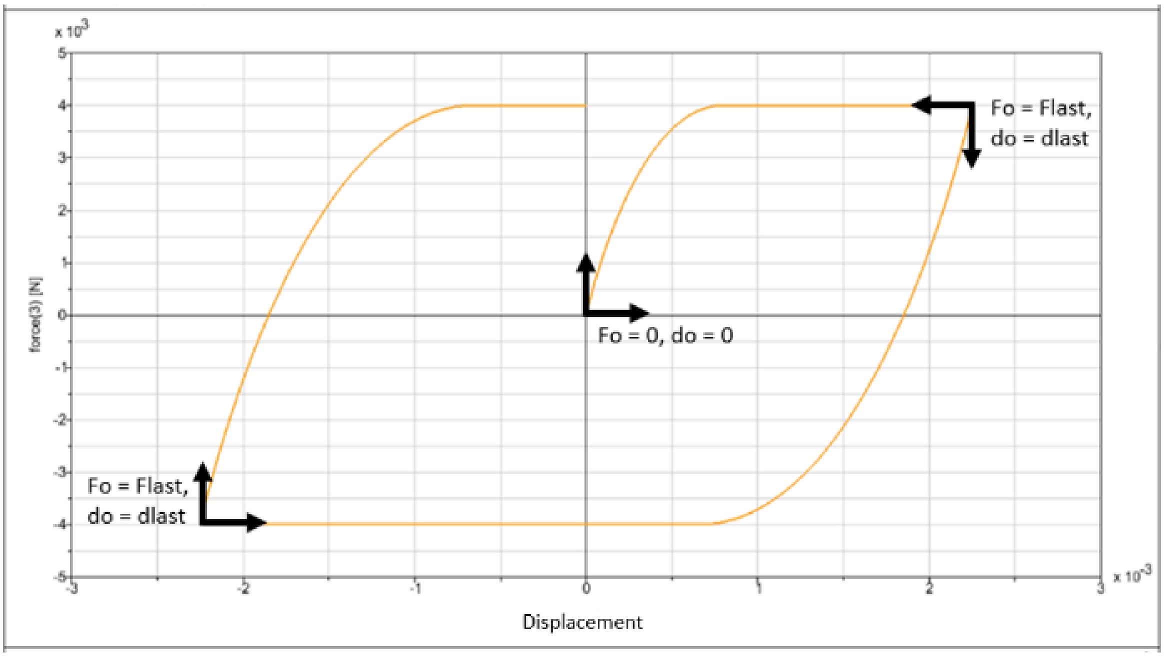

Figure 7: Illustration of changing direction for each cycle

There are challenges at the end of the first cycle, when the change in velocity occurred and the condition for change in direction is detected. The shifting of values had to be done in the exact same step, otherwise the error will occur if there is a difference in time step in changing the values according to the condition for the velocity and direction is applied.

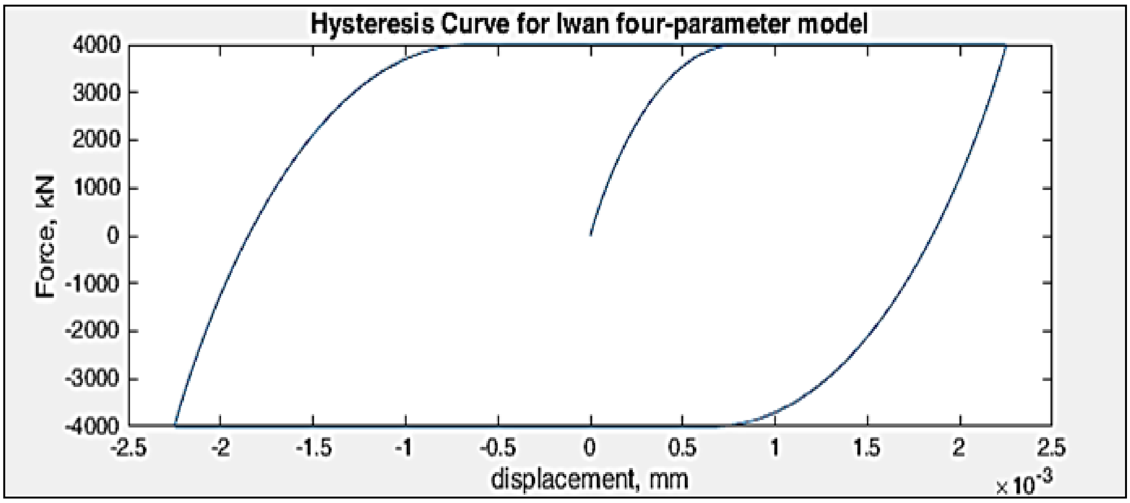

Figure 8: Hysteresis curve for the RIPP joint model of the 4-parameter Iwan model (MATLAB, 2017)

The initial states zero being defined, there are two states in the system; Sticking, as when the force is applied it starts to stick for a certain period of time. This state, where local stick and slip zone exist simultaneously in the contact area, is called micro-slip. And when more and more elements exceed their slip limit, it reaches the maximum force then it starts slipping continuously without any further change in the force. When there is load reversal, the cycle starts again but in a negative direction, showing negative force and displacement values. The load reversal or negative cycle is the scaling of the first cycle. The third cycle resembles the same behaviour and it shows the same curve as the first cycle, with the only difference being that the last cycle starts from the point where the negative cycle is complete.

4.0 USER ROUTINE FORCE ELEMENT

The system has been modelled by user routine in SIMPACK Solver. To see the smooth behaviour of force and displacement, the following initial function is used.

4.1 Model Setup

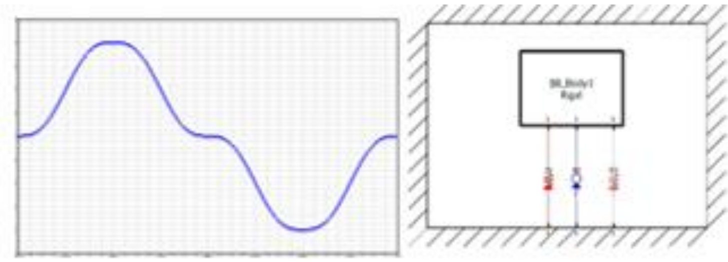

Figure 9: (Left); Input condition of SIMPACK Solver, (Right); 1-D Representation of Iwan Force element with a single mass-damper

The same parameters are chosen based on a 304 Stainless Steel lap joint in Table 1. The parameters, input, output and working values are declared as local variables and initialized to run for solver. Descriptive states are used to store the values. An additional global array will be used to store the value of the current time step. The current time step decides if the last step was successful and if the descriptive state needs to be updated. There are challenges in using the descriptive states and storing of values from the last step. As the force double additional is defined with the dimensions. As the additional double array reads the last step value in every iteration and set the value to descriptive states, only and unless it is a successful run. So additional double array passes the last successful value to the descriptive state and if the solver run is unsuccessful, then it will just access descriptive state, but does not define the value to the state.

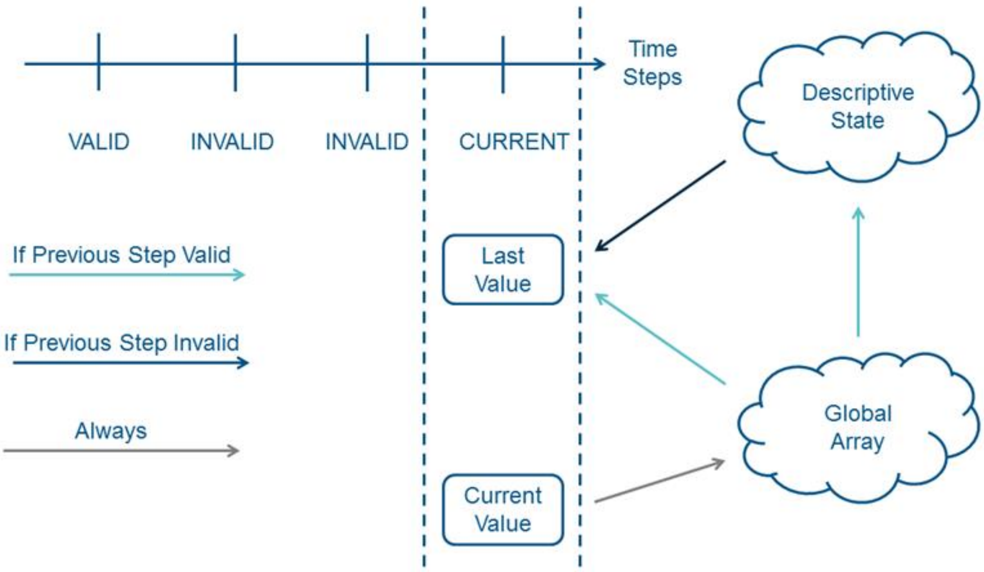

Figure 10: Illustration of storing values by using descriptive states

4.2 Comparison of MATLAB Model and SIMPACK User Routine Model

- The behavior and the response of both curves obtained are the same.
- The transition point from micro-slip to macro-slip in the positive and negative cycle is the same.
- The maximum and minimum forces within the loading cycle are also the same.
- The change in dissipation parameter will change the shape of the curve, the lower the parameter, the smoother the curve.

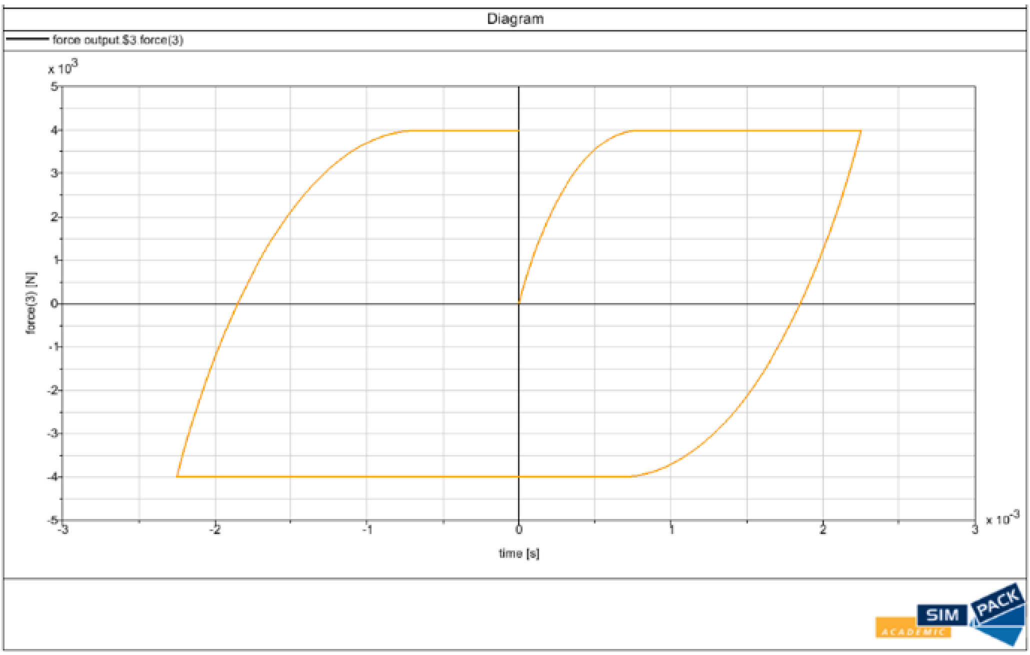

Figure 11: The diagram represents the hysteresis curve of four-parameter Iwan model in SIMPACK user routine, x-axis, displacement (mm) and y-axis Force (kN)

4.3 Variation in Parameters

The energy dissipation parameter β selection is usually based on the shape of the hysteresis loop. The roundedness of the hysteresis curve in Figure 11 depends on the value of β. A particularly simple representation of the system is obtained in Figure 12 when β = 1. It will be noted that the response curves have a general soft character which is typical of most hysteretic models.

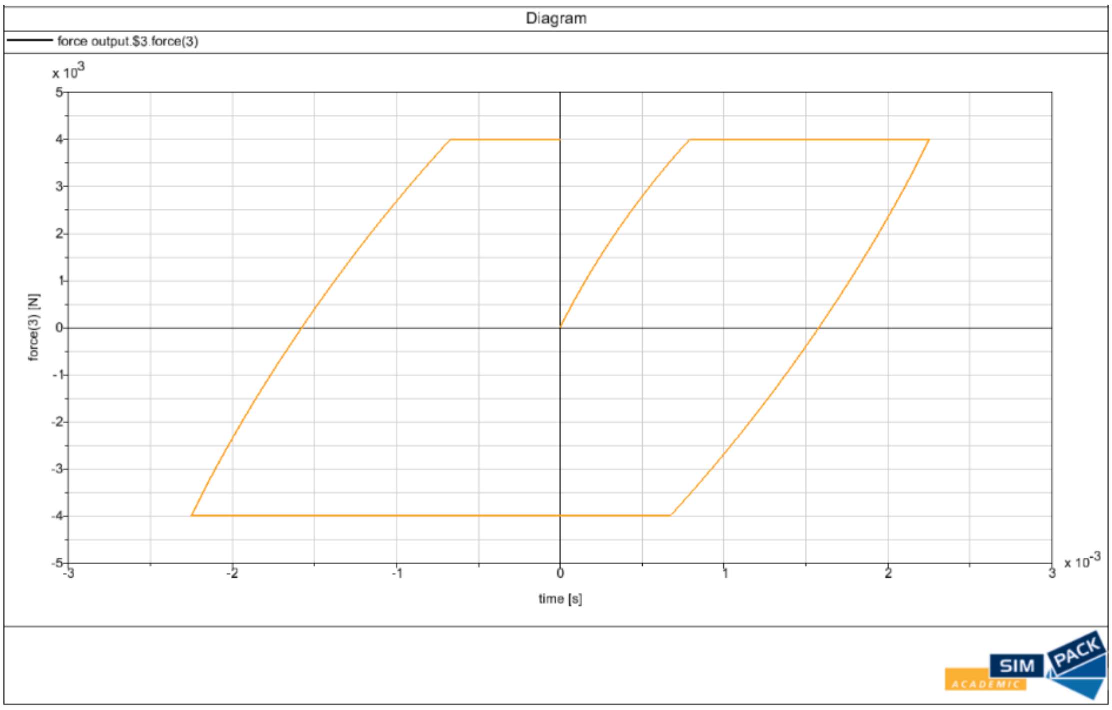

Figure 12: The 4-parameter Iwan model in SIMPACK user routine force element with β = 1

In comparing the four-parameter Iwan model to the five-parameter Iwan model in Brake (2016) with ϴ = 1, all other parameters are the same as before. Both models show the same tangential stiffness. As with ϴ = 0.75, the five-parameter Iwan model has lower peak force, due to ϴ less than 1. One unexpected consequence of this is that the maximum and minimum forces vary from one loading cycle to the next as shown in Figure 13.

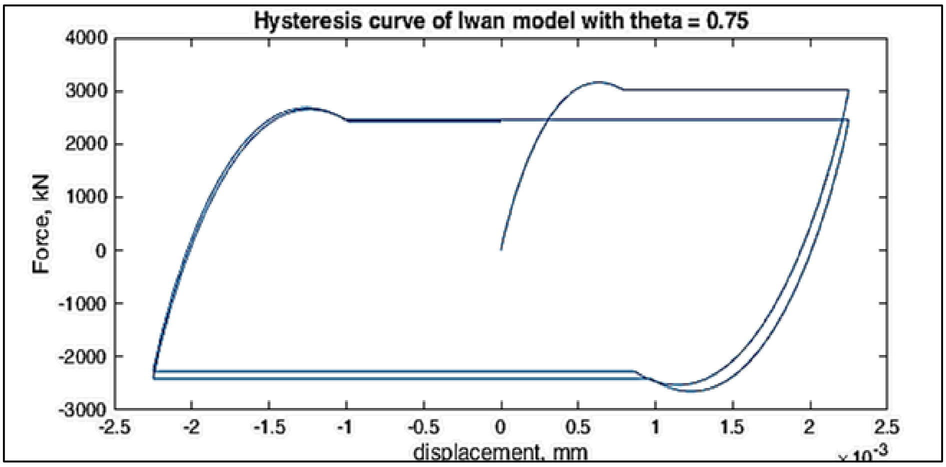

Figure 13: Hysteresis curve for the RIPP Joint model of the five parameter Iwan model with ϴ = 0.75 (MATLAB, 2017)

5.0 EXTENSION FROM 1-D TO 3-D MODELLING

Segalman's four-parameter Iwan element is one-dimensional, and it has been extended to thee-dimensions, because typically a joint model is coupled with multiple Iwan elements all oriented in the different translational and rotational directions. However, it is challenging to determine a unique set of parameters for each of these elements and depending on the joint behaviour, not all directions may be necessary. For the joint models, the Iwan elements are oriented along the axial (x) direction of the beam since the investigated bending modes were expected to exercise friction along this direction predominantly.

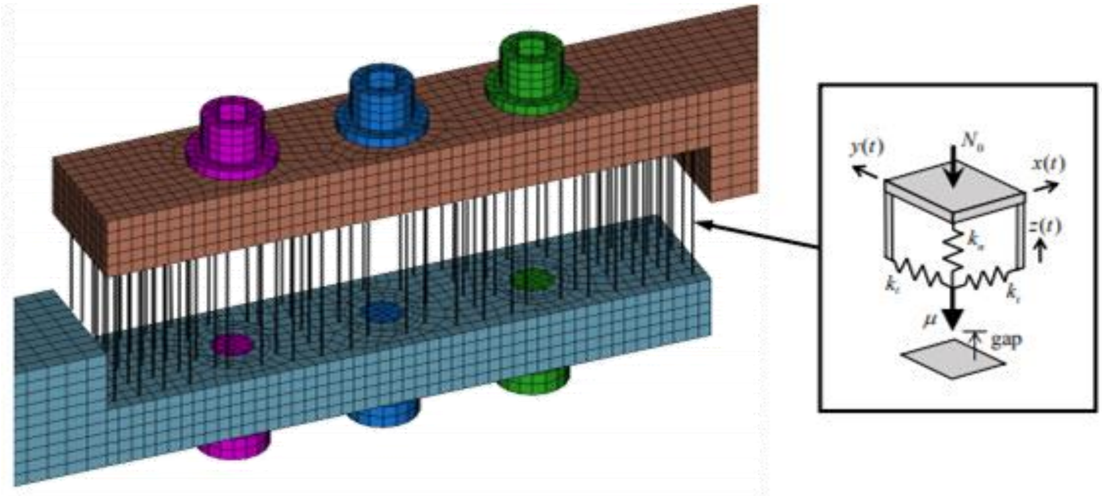

Figure 14: Representation of springs in three directions (Lacayo et al., 2019)

The joint model consists of uncoupled meshes for the two beam components as well as for the bolt assemblies. The bolts are included in the model to capture their stiffness and mass effects on the overall model response, and they are the mechanism that clamps the two beams together and applies a pressure on the contact interface. The bolt, nut, and washer assemblies are each lumped into the model since slipping is unlikely to occur between these parts when clamped due to the extremely high contact pressure. Here in Figure 15, the strategy to define the radial components has been mentioned, as the radial component consists of two tangential components. The initial condition and the condition for all four quadrants has been defined.

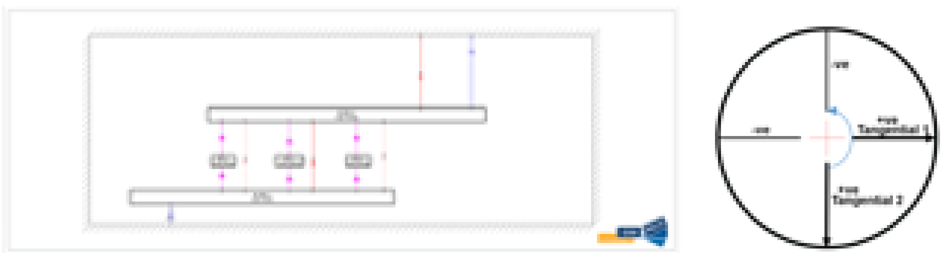

Figure 15: (Left); 2-D view of lap joint connected with three screw, (Right): Initial starting point and the positive negative quadrants for radial values.

It is important to define the condition for the angle as Force output is dependent on the sine and cosine angle for calculation of both components. The angle between both tangential components is calculated by dividing tangential one by tangential two. So when any one component becomes zero, the angle will be zero.

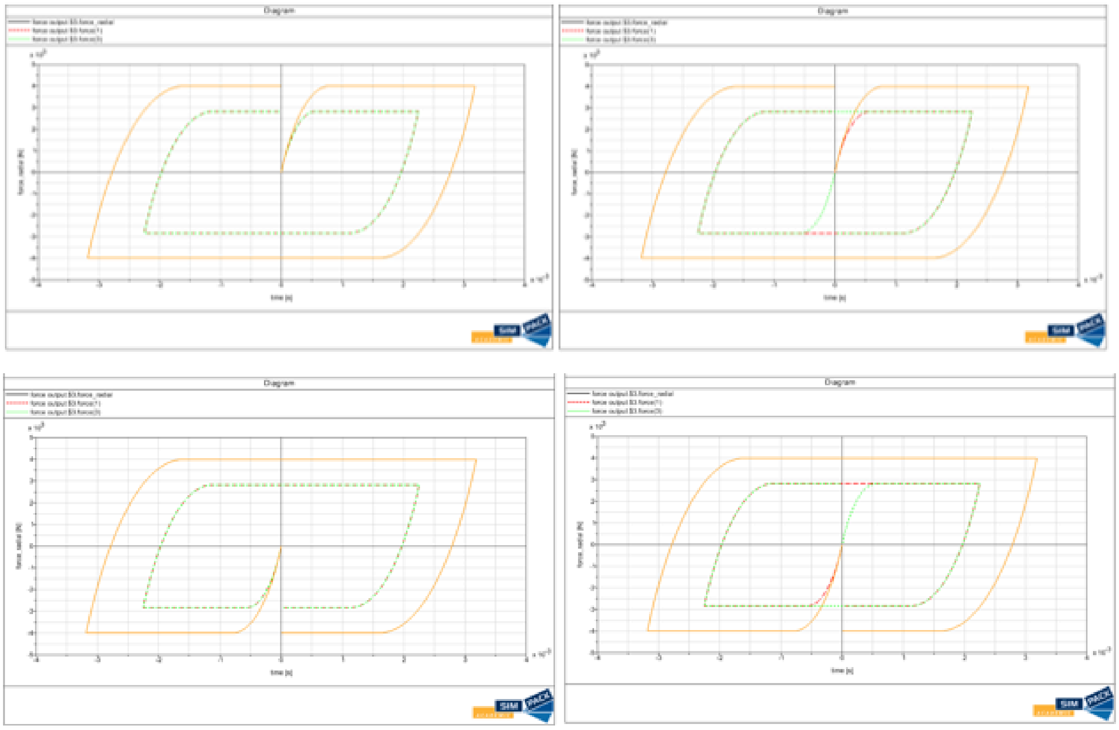

Figure 16: The hysteresis response of tangential x-component (red dotted lines), tangential y-component (green dotted lines) and collective response of both components (orange line) in all 4-quadrants

When only a fraction of all the sliders starts slipping, the Iwan element exhibits micro-slip behaviour. When the final slider passes its slip threshold, the Iwan element as a whole enters macro-slip and follows a constitutive relationship equivalent to Coulomb friction until load reversal.

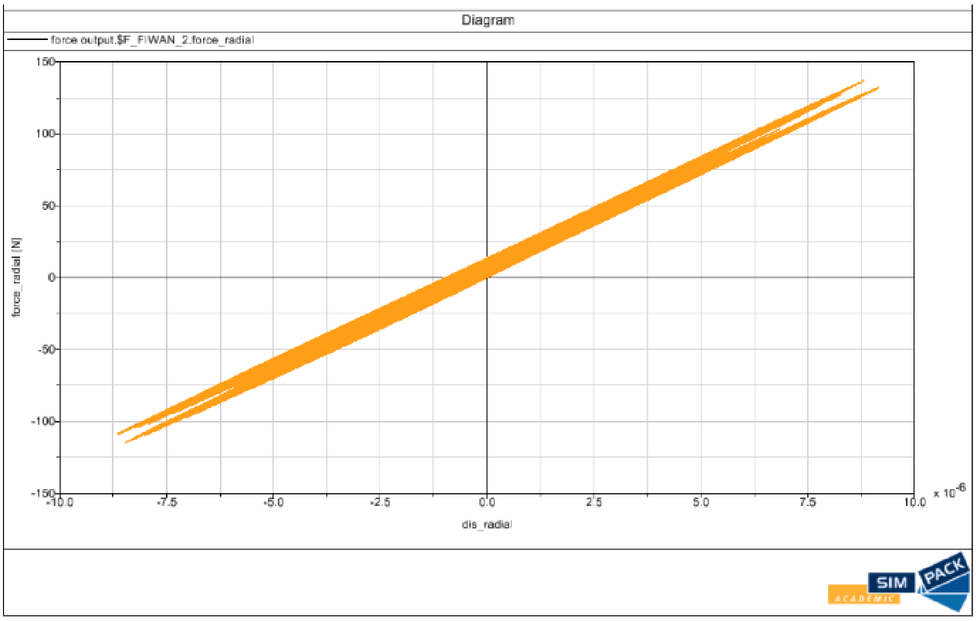

Figure 17: Iwan model at the interface of a Lap Joint

6.0 MODE SHAPE ANALYSIS

To address this, a quasi-static technique, the amplitude dependent frequency response has been calculated and plotted for different values of amplitude. As the forcing magnitude increases, the peak resonance point shifts downward in frequency (softening) and the peak becomes shorter and wider (damping increases). Additionally, the shape of the peak loses symmetry and becomes slightly skewed towards the left, which reflects the softening behaviour of the beam with increasing response amplitudes. These forced response trends are highly typical in structures containing bolted joints and indicate a certain amount of sliding in the contact interface.

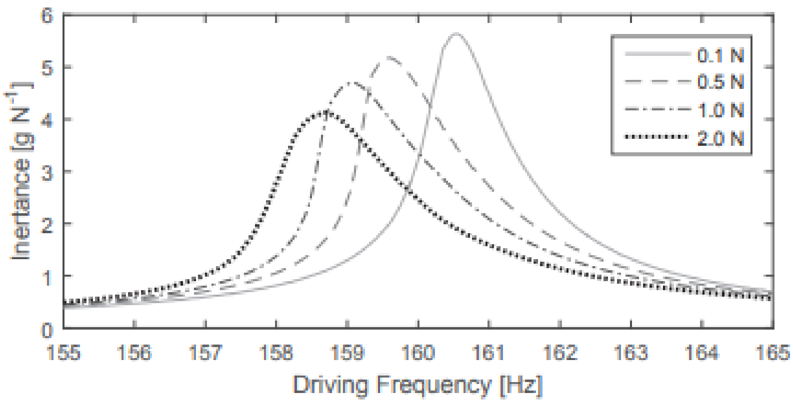

Figure 18: The amplitude dependent frequency response

7.0 SUMMARY

The analytical based Iwan model for the contact interface was expanded upon to facilitate model updating against forced response measurements on a simple mass spring structure in one dimension and to extend the model from one-dimensional to three-dimensional. The symmetric hysteresis loop results have been obtained on application of constant force. The roundedness of the hysteresis curve is dependent on energy dissipation parameters. The force amplitude dependant frequency response is then calculated and it shows that at constant frequency, by increasing the amplitude of the force, the acceleration increases but the ratio of acceleration to force decreases. This model shows an efficient solution for the simulation and auralisation of drive-related noise in electric vehicles as it has less degree of freedom as opposed to an FE solution, but therefore allows the calculation on system level. It is shown that dominant phenomena and the hysteresis response can be identified. This research work can serve as the reference for the model updating and validation of beams with jointed structures and housing of transmission system.

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