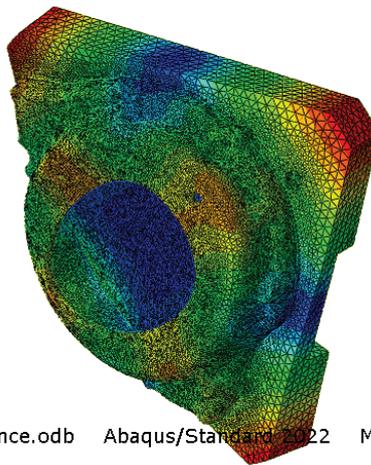
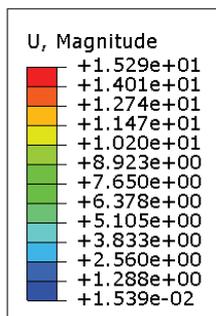


# Virtual Evaluation of Machining Fixtures for Flexible Manufacturing Systems, VEMF-FMS

Public report



ODB: BH\_fixture\_sequence.odb Abaqus/Standard 2022 Mon Dec 02 14:41:52 W. Europe Star  
Step: Step-5  
Mode 1: Value = 7.16723E+07 Freq = 1347.4 (cycles/time)  
Primary Var: U, Magnitude

Project within FFI Circularity

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Date 2025-05-30



Fordonsstrategisk  
Forskning och  
Innovation

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### FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: [www.ffisweden.se](http://www.ffisweden.se)

# 1 Summary

This project aimed to establish a roadmap for developing a virtual environment to support the design of machining fixtures—an essential step in transitioning from dedicated manufacturing systems to sustainable Flexible Manufacturing Systems (FMS). The shift is critical for improving circularity in manufacturing, enabling machinery to be reused across product changes rather than being discarded.

The project began by collecting industrial viewpoints through meetings with partners. It then evaluated the current state of fixture design technologies and explored advanced simulation methods for modeling the dynamics of assembled structures. A key focus was on incorporating nonlinearities at contact surfaces, which significantly affect fixture performance.

Finite Element (FE) models and machining simulations were developed to include these nonlinear effects. A major technical effort was devoted to implementing "User Elements" for commercial finite element software, capable of modeling contact nonlinearity, particularly micro-slip behavior at joints. These nonlinearities are shown to influence both the vibration stability and precision of machining operations.

Experimental methods were also explored to extract dynamic properties of structures. Tests included the use of impact hammers, piezo discs, accelerometers, and tensile testing machines. These experiments confirmed the persistent presence of nonlinear behavior in built-up assemblies and provided valuable data for simulation model calibration.

## 1.1 Key Findings

**Need for Predictive Tools:** There is a growing need for more accurate prediction of fixture performance, especially given the shortage of experienced fixture designers, the increasing frequency of product updates and increasing the complexity of products and fixturing systems. These predictive tools are valuable in circular use of production equipment, as production moves away from dedicated manufacturing systems towards flexible manufacturing systems.

**Iwan Elements:** These provide a robust method for simulating micro-slip behavior. The Modal Iwan model, in particular, offers a practical approximation for analyzing assemblies with many joints and degrees of freedom.

**Integration with Machining Simulations:** Modal Iwan models can be effectively combined with machining simulations to predict the outcome of operations, improving both design accuracy and process reliability.

**Nonlinear Joint Behavior:** Incorporating nonlinear behavior at joints is essential for accurately predicting machining system stability and avoiding unwanted vibrations. Micro-slip at joints in some cases can also degrade machining precision.

**Data Gaps:** There is a lack of a comprehensive database for selecting Iwan parameters based on surface conditions and material combinations. Developing such a resource would significantly enhance simulation ease and accuracy.

**Research Legacy:** A notable body of work by Segalman et. al [1-4] and Brake et. al [5] for Sandia National Laboratories has contributed foundational knowledge in this area. However, the associated Sierra/SD (Salinas) FE software is not publicly available.

In this project, we evaluated the contact nonlinear dynamics of a scaled Brake-Reuss beam [6] assembly made of aluminum. This approach could be extended to evaluate the dynamics of more complex assemblies, as found in machining fixtures.

## 1.2 Recommendations

- Develop a shared data bank for joint parameters considering surface conditions (e.g. manufacturing operation, roughness and waviness) and material combinations to support fixture design.
- Expand experimental validation using more comprehensive and precise excitation and measurement methods (e.g., electromagnetic shakers, laser vibrometers).
- Enhance collaboration across academia and industry to scale up development efforts and integrate findings into practical design tools.

## 2 Sammanfattning på svenska

Fordonsindustrin genomgår en omställning mot flexibla tillverkningsystem (FMS) som drivs av ökade krav på hållbarhet, produktvariation och frekventa omkonstruktioner. I jämförelse med traditionella dedikerade tillverkningsystem erbjuder FMS en ökad anpassningsförmåga, skalbarhet och cirkularitet. En stor utmaning i införandet av FMS är utformningen av robusta, precisa och stabila fixturer för bearbetning, vilket idag är kostsamt och tidskrävande då det kräver omfattande trial-and-error testning. För att adressera detta studeras metoder för att modellera fixturers mekaniska beteende. Särskilt fokus läggs på att prediktera icke-linjära dynamiska effekter som uppstår på grund av mikroglidning och friktion i kontaktzoner mellan fixturelement och arbetsstycke. I detta syfte utvecklas sk. Iwan-modeller som möjliggör prediktering av strukturers amplitudberoende styvhet och dämpning vilket i sin tur tillåter en mer tillförlitlig modellering av bearbetningsprocesser.

Projektet de övergripande målen att:

- förstå utmaningarna i dagens fixturdesign,
- utvärdera kontaktmodeller (t.ex. Iwan) för att förutsäga det dynamiska beteendet hos sammansatta strukturer,
- integrera dessa modeller i kommersiell finita elementprogramvara,

- utveckla numeriska modeller av bearbetning som tar hänsyn till icke-linjärt dynamiskt strukturbeteende.

Forskningen har därmed fokus på den senaste tekniken inom fixturdesign, befintliga modellers noggrannhet och dess integration för simulering av bearbetning samt experimentella metoder för kalibrering av kontaktmodeller.

I projektet har modala Iwan-modeller identifierats som effektiva för modellering av det dynamiska beteendet hos sammansatta strukturer. Modellparametrar kunde extraheras via "stop-sine"-tester och dragprovning. Vidare utvecklades användardefinierade finita element (Abaqus UEL) med vilka sammansatta systems olinjära respons, med avseende på dämpning och egenfrekvens, kunde modelleras. Simuleringar visade att fixturens dynamiska beteende påverkar stabiliteten i bearbetningssystem och att mikrogliedning uppstår även vid stabil bearbetning.

Projektets resultat stödjer EU:s och Sveriges hållbarhetsmål genom införande av cirkulära FMS och digitaliserad tillverkning som främjar en mer ekonomisk och miljövänlig produktion. Projektets resultat förbereds för publicering, och delar av det experimentella arbetet har genomförts som del av examensarbete vid Högskolan i Skövde.

### 3 Background

The automotive industry is currently undergoing a significant transformation, characterized by a surge in new product introductions, frequent redesigns, and increasing sustainability demands. These shifts necessitate a transition towards Flexible Manufacturing Systems (FMSs) to adjust to the evolving market landscape characterized by low-volume, high-variety production. Traditionally, Dedicated Manufacturing Systems (DMSs) optimized for high-volume, low-variety production have been predominant in manufacturing powertrain components. However, the transition to FMSs offers adaptability, circularity through the reuse of manufacturing equipment, and scalability in operations, enabling companies to effectively meet evolving market demands.

For OEMs and subcontractors such as Aurobay and Leax, specializing in internal combustion and hybrid powertrains, the adoption of FMSs is particularly critical. These companies aim to reduce their environmental footprint while remaining competitive in the market. An important aspect of producing products with FMSs is designing proper fixtures, that hold components securely and accurately during machining. The fixture design is particularly challenging and time-consuming, due to the requirements for automation, precision and vibration stability (or robustness against self-excited vibrations known as chatter). Satisfying these requirements is not trivial and often companies face costly, trial-and-error campaigns with physical prototypes to arrive at a robust fixture design. Avoiding these iterations by evaluating fixture performance in a virtual environment will offer notable cost and time savings for these companies, but developing reliable virtual assessment tools is challenging, due to difficulties in predicting the stiffness and damping properties of the fixture assembly, which are affected by complicated nonlinearities resulting from contacts across the workpiece and the fixture. Recent methods in modelling the dynamics of contacts and joints have shown some promise in predicting these

behaviours. Considering these points, the proposed research aims to assess the performance of these methods, for fixture design and evaluating machining outcomes for FMSs.

Central to the success of this research is assessing the accuracy of the tools and modelling methods to predict form errors and vibrations in machining processes, by modelling the dynamic response of the machining systems, including the fixturing nonlinearities, thus eliminating design iterations and adjustments of fixtures. Such tools will enable companies to optimize fixture design and machining processes in a virtual environment, leading to reduced production lead times, minimized material waste, and improved product quality. This will also facilitate timely component design change proposals, i.e. contributing to the manufacturability of these components.

In this project, Study of the state of the art led to selection of Iwan elements [7] for representing the micro-slip in mechanical joints. Employing Iwan's model, in simulation of machining, showed its capabilities in predicting the dynamic behavior of a simple machining system. This contact modelling method was also evaluated in time-domain, Finite Element modelling of time response of a simple beam assembly where joint parameters were obtained experimentally, demonstrating amplitude dependent damping and natural frequency shift (due to reduction in stiffness at higher amplitudes). Similar procedures could be extended to industrial fixturing cases.

This project was a necessary step before committing to a full-scale prospective project to offer a comprehensive virtual tool for assessing the machining performance of fixtures.

## **4 Purpose, research questions and method**

Full implementation of the virtual environment will contribute to the economic, agile, and environmentally friendly circular utilization of production machinery, by facilitating the adaptation of FMSs, which in return will contribute to the long-term sustainability of the automotive industry and the reduction in fossil fuel consumption outlined by both EU and Swedish sustainability goals and legal requirements.

For this pre-study, the following research questions were identified:

- Q1. What is the state of the art in design of fixturing setups in collaborating industries?
- Q2.1 How well the state-of-the-art contact models help to predict the dynamics of built-up structures used in machining?
  - Q2.2 How well these models could be adapted to be used in commercial FE software to predict dynamic behavior of geometries encountered in fixturing and machining?
  - Q2.3 Which experimental methods are available for calibration of the mentioned models.
- Q.3 Which phenomena could be observed when combining contact models in simulation of machining operations?

Interviews and workshops were used to answer Q1. Q2 was answered by a combination of state of the art review, experimental investigation and Finite Element Simulation. Q3 was answered by simulations in MATLAB environment.

## 5 Objective

The purpose of this pre-study was to assess the feasibility of establishing a virtual process-planning tool supporting the design stage of fixturing and tooling and to address key challenges in predicting the performance of machining fixtures and assemblies for FMSs. Specifically, the pre-study focused on evaluating existing technologies, analyzing new approaches, and identifying opportunities to successfully address the current research gap in predicting the dynamic behavior of fixture assemblies, enabling the prediction of machined component quality.

Specifically, we had the following objectives:

- Objective 1.1: Analyze and evaluate the challenges encountered during the transition towards circular FMS to accommodate low-volume manufacturing across a broader product spectrum.
- Objective 1.2: Analyze and choose a representative or challenging [past/ongoing/future] product, along with its corresponding Flexible Manufacturing System (FMS) design and required fixturing
- Objective 2: Evaluate the feasibility, efficiency and accuracy of available methods for modelling the dynamics of machining fixtures and predicting workpiece-fixture assembly dynamics, including stiffness and damping properties.
- Objective 3: Develop machining models that account for fixture contact nonlinearities and explore possible simplifications or approximations for efficient calculation.

The objectives 1.1-1.2 were covered without change. In terms of objective 2, we mainly focused on one dominant approach, i.e. Iwan elements, and comparing its performance against experiments. In terms of objective 3, considering that the selected method (Iwan method) was sufficiently fast, the focus moved on studying various scenarios (e.g. intermittent cutting vs. continuous cutting) rather than focusing on simplification and increasing the speed of calculations.

## 6 Results and deliverables

The results below are numbered correspondingly to the objectives described in the project:

### 6.1 State of the Art

Result 1.1: The project overviewed the status and needs of fixture design at collaborating industries. An important trend is the use of "zero-point" clamping systems.

Result 1.2: A bell-house (connector between the electric motor and gearbox) and its fixture was selected as the case-study object. Dynamic characteristics of each component was obtained using impact hammer tests along with Finite Element simulation of each component separately and then in an assembled form ready for machining.

Result 2:

The literature review pointed to modal Iwan models [4, 5, 7] as the state of the art in efficient modelling of built up structures. Iwan element is a well-established method for modelling the micro-slip behavior that happens in the lower pressure contact zones involved in a joint, while the regions joined under high pressure just deform elastically.

## 6.2 Experiments and Simulation

Result 2: It was possible to extract key parameters for Iwan elements using tests such as "stop-sine", in addition to using tensile test machine at HIS to obtain tangential stiffness and sliding limits in a sample joint. Stop-sine tests were performed by simultaneous control a function generator (that excited a piezo disk) and a data acquisition system that collected vibration signals.

Result 2.1 We developed finite element simulation of assemblies considering the nonlinear behavior of joints. The simulation was possible by writing a custom ABAQUS Standard "User Element" subroutine for implicit dynamic simulations that implement the "Iwan" element behavior. The simulation was able to reproduce amplitude dependent (non-linear) damping and natural frequency shift as observed in experiments.

Result 3: We were able to simulate a machining system with Iwan element that represents a joint, with parameters that were extracted from experiments. We could show that the stability of the system is strongly affected by the joint. Also, in stable cutting, the micro-slip would lead to minute overall microslip of the Iwan joint.

As mentioned in the previous section, while some objectives were updated considering the observed realities faced at the field, the overall goal of identifying and testing the building blocks of a virtual fixture evaluation system is achieved.

## 7 Dissemination and publications

We have obtained publishable results in answering the research questions, which we are preparing to publish/present in academic publications/conferences. Other dissemination and publication details are as follows:

### 7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	In addition to participating companies, the results of the project is planned to be presented in Driving Efficiency and Innovation through Simulation and Optimization event at Assar Innovation Arena.
Be passed on to other advanced technological development projects	X	Expertise in development of User Elements for FE software along with experimental hardware/software for characterization of systems with contact nonlinear dynamics.
Be passed on to product development projects	X	If we consider the virtual environment as a product, then in future projects the TRL of this product will increase to eventually be deployed to the market
Introduced on the market		Market introduction was not planned for this pre-study.
Used in investigations / regulatory / licensing / political decisions		Not applicable.

## 7.2 Publications

Results of the project has been collected continuously and documented during the project. Publications are being prepared at present. The majority of experimental results are documented as bachelor's level thesis work within mechanical engineering at University of Skövde.

## 8 Conclusions and future research

In conclusion we identified opportunities and challenges of using Iwan elements to model dynamics of a built-up structure used for machining. We tried measurement methods to calibrate parameters of this model, programmed "User-Elements" in a commercial FE software and evaluated the interaction of an Iwan element in a continuous and intermittent machining. Reaching these results show the technological feasibility of developing a virtual environment for evaluating machining fixtures, however, the following fields and issues are identified to be further investigated in subsequent projects:

- Developing a data bank for joint parameters considering commonly used surface conditions (e.g. manufacturing operation, roughness and waviness) and material combinations to support fixture design.
- Full-integration and interconnection of modal-Iwan approach with finite element and machining simulation.
  - During the pre-study, possible methods are identified to make this process computationally efficient, in face of contact nonlinearity. This will allow time efficient virtual testing of various fixture designs and configurations.
- Integration of the experimental measurements from a machine tool equipped with zero-point fixturing capability, CAD model of the fixture and the tool and tool holder, blank and the part, to estimates the dynamic parameters of the workpiece mounted on the machine tool using the fixture.
- Enhancing experimental characterization using more comprehensive and precise excitation and measurement methods (e.g., electromagnetic shakers, laser vibrometers).
- Final workpiece surface precision prediction, as the simulations in the pre-study only traced the tool-workpiece engagement deviation without registering and updating the points representing the workpiece.
- Updating the workpiece dynamics during material removal, using FEM.
- Investigation of application of Artificial Intelligence in robust fixture design.

## 9 Participating parties and contact persons

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