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Model-based estimation of contact forces

Dirk Söffker
Dynamics and Control, Gerhard-Mercator-University Duisburg, D-47056 Duisburg, Germany
soeffker@uni-duisburg.de

Heinz Ulbrich
Applied Mechanics, Technical University of Munich, D-85748 Garching, Germany
ulbrich@amm.mw.tu-muenchen.de l

***Abstract**: The paper summarizes different experimental results of the authors cooperation. Core of the joint work is the application of a model-based estimation technique for estimation of unknown impacts acting to elastic structures. Experimental results of the observer-based estimation of unknown impacts are presented.*

***Keywords**: Impact, Elastic Structure, Observer, Estimation*

Introduction

The control of mechanical structures has been the focus of several scientific and industrial efforts of the last decade in the area of robotics, vehicle- and rotor dynamics. Actual works are focused on flexible (space) structures concerning aspects of practicability/realizability and precision. In all these areas, the classical fields of mechanics/dynamics and control theory as well as data processing are connected. Advanced control approaches usually need knowledge about the system to be controlled. This can be realized e.g. by the way of mathematical models (e.g. sets of differential equations) as the base to design observers or regulators/compensators.

Effects of friction, backlash or impacts often occur in elastic structures. The existing models mainly describe the effects themselves, so complete model descriptions usually are not available. Due to these effects, the system behavior in operation may switch between that described by linear and that described by nonlinear formulations. These effects especially aggravate the systematic control of such system types. Impacts have strong effects on the vibrational behavior of flexible structures. As an example, rubbing effects between rotor and housing, or rotor and safety bearing should be mentioned. The contribution does not focus on the analysis of these flexible systems with impacts, but on the development of a suitable estimation technique. The typical restrictions of this kind of machines or rotordynamic structures are that measurements of the impact can not directly be taken. This means that impact forces or torques can only be obtained indirectly via the resulting vibration effects. The task of an advanced control system should be not only the control of the vibrational behavior of the system itself, but also the compensation of the impact force. Chen (1993) applied a nonlinear sliding mode technique to control the motion of a flexible beam and the contact motion. The idea of the proposed technique works with two steps: first to reconstruct the contact force as good as possible and in a second step to apply disturbance attenuation techniques to reject the disturbance (=the affecting contact force). This contribution deals with the first step. A comparable technique was published by Hollandsworth and Busby (1989). Core of their contribution is the use of an inverse technique. Accelerations are used as measurement. Their results show

- that the quality of the impact force estimation is very good if the measurements are done directly at the contact position,
- that the quality of the estimation strongly depends on the measurement position close to the contact point, and
- that the estimation of the correct impact force amplitude seems not to be possible using measurements beside the contact point.

This contribution also deals with a model-based approach and tries to overcome the mentioned difficulties. Here a PIO-technique is applied to estimate the contact force as well as contact displacements using a minimal number of measurements (using one or two sensors) applied beside the contact position. For principal investigations a simply to realize experiment has been done. Simulation results are shown in previous publications (Abicht, 2001). The systems to be considered here is shown in Fig. 3 and 8.

Nomenclature

A = system matrix
Ao = nominal system matrix
B = control input matrix
C = output matrix
L1 = gain matrix of the observer, related to the system state
L2 = gain matrix of the observer, related to the system state extension
L3 = design matrix of observer design
n = vector of unknown inputs
N = input matrix of the unknown inputs
D = pin diameter, diameter, m
f = state vector extention of the PIO, used for estimation of unknown effects n acting to nominal known dynamics systems
x = state vector
y =output vector
z = mechanical state vector

Model-based Estimation Technique

The idea here is to apply a model-based approach based on a Proportional-Integral-Observer-technique (PIO) to reconstruct unknown external inputs. The base of this technique – the disturbance observer (DO)- is well known for the application of modeled disturbances (known external effects acting to the considered system) (Andersen, 1989). The PIO technique realizes a special modification of the DO and is used for the detection of faults or for determination of nonlinear effects acting on dynamic systems (like friction, backlash) as a modern Fault-Detection-Isolation (FDI)-scheme. The main important aspect is that no model for the affecting disturbance is necessary. This allows the application to those problems, where no model is available or the application of a known model is not useful (e.g. because of complexity). The structure of the PIO is illustrated in Fig. 1.

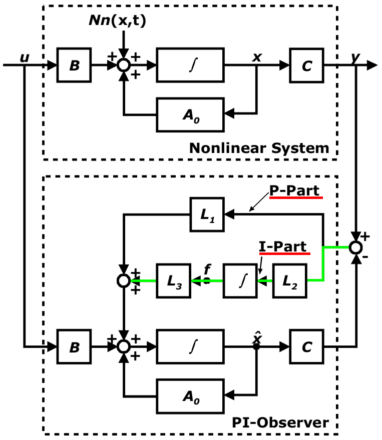

Figure 1. Structure of the Proportional-Integral Observer (Söffker et al., 1995)

In contrast to the classical Luenberger observer the PIO technique can be understand as an extention. Therefore additional design states are introduced which are used for integral feedback of the observer error. In combination with a high-gain approach, this will lead to the fact, that the additional additive effects acting on the system (here **Nn**) which are not connected to the known system dynamics (represented by **Ao**) will be pressed into the system extension. The observer gives estimations **x-ha**t for the system state **x** and additionally estimations **f** for the unknown effects **n** acting to the system itself. Details are given in (Söffker, 1995). Actual results also can be found in (Söffker, 1999).

The assumptions of the PIO are:
- The system model **Ao** (for mechanical systems: **M,D,K** –matrices) is assumed as to be known.
- The location of the acting unknown effects acting as forces or moments to the structure has to be known.
- The extended system (cf. (Söffker, 1999) must be observable.
- The number of acting unknown effects has to be smaller or equal to the number of independend measurements (Rg(**N**) less or equal than (Rg(**C**)).

The advantages of the application of the PIO are:
- Beside of knowledge of the location of the acting unknown effects no further knowledge about the effects is assumed as to be known (neither the exact model nor assumptions about the dynamics).

The leads to the fact that the PIO-technique can be easily applied to (observable) mechanical structures as a virtual measurement device of those unknown effects, which
- should be estimated for compensation or
- are of other interests, for example for model validation (of contact effects) etc. The effects can be shown as
    - a time function (shown in Fig. 6,7,9),
    - state dependend effects
      (simple case: linearity of contact elasticity (Fig. 2 left;
      complex case: adhesion characteristic (Fig. 2 right)

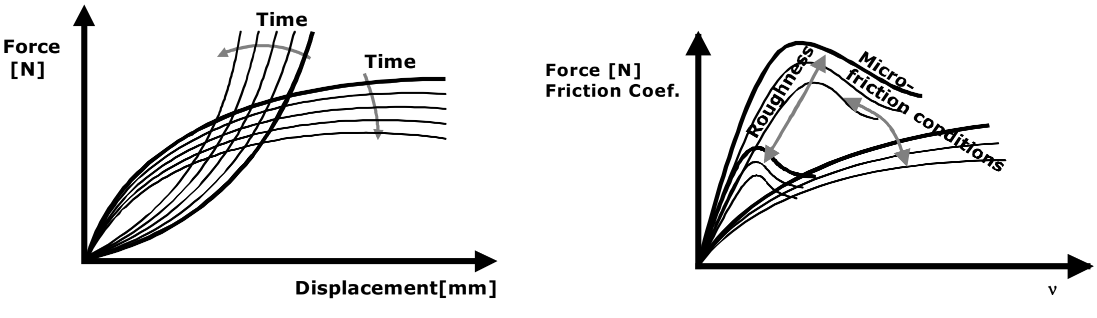

Figure 2. Unknown effects to be estimated with PIO technique (combined with further estimations or measurements) (left: spring characteristic, right: adhesion characteristic)

Estimating contact forces acting to a fixed beam

A test-rig has been build up at the Institute of Mechanics at the University of Essen (Abicht, 2001)

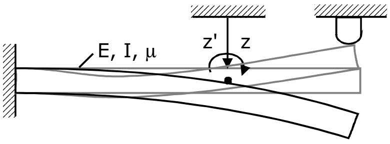

Figure 3. Scheme of the mechanical system used to PIO validation purposes

The test rig itself is given with Fig. 4. It allows the experimental validation of the proposed observer technique for estimation of the contact forces. The experimental results of the first step are given in Fig. 6 to 7.

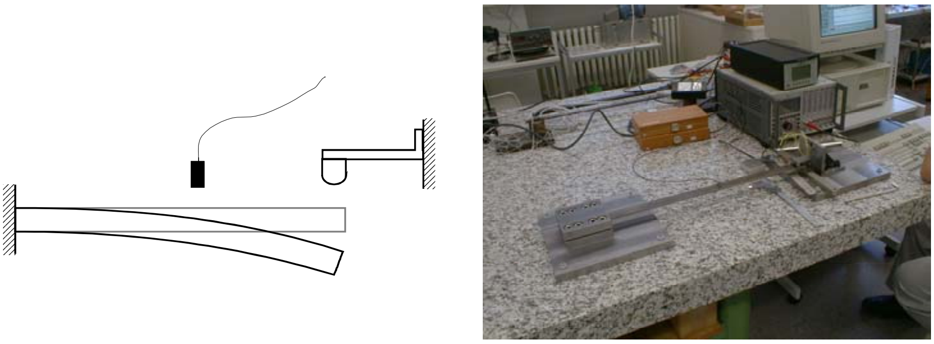

Figure 4. Test rig (University of Essen) and measurement application

The length of the beam is 505mm. The beam is modeled using 5 equal finite beam elements each of 98mm length. The neglected mass at the top of the beam is considered as a concentrated mass. The contact point is at 490mm, the displacement measurement is taken at 392mm. The beam material is steel and the retangular cross-sectional area is of 25mm x 5mm. The gap at the contact point is 1mm. The displacement measurement is realized using a non contacting optical displacement measurement system in combination with the triangulation method. The force measurement is realized using a standard impulsehammer. The contact is realized with different tips (steel,plastic and two types of vinyl). The used different tips for the contact are given with Fig. 5. The measurements have been done at the University of Essen (with the first author), the application of the PIO to the measurements at the University of Wuppertal (with the second author).

Figure 5. Different tips of the impulse hammer (used as contact device)

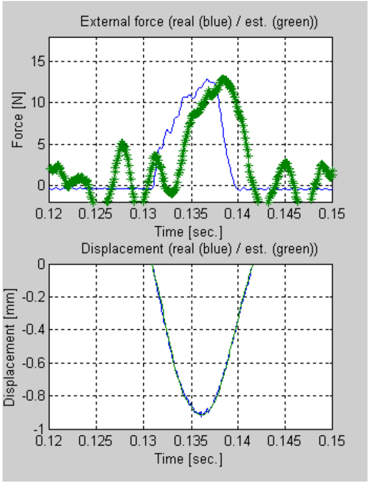

Figure 6. Contact force estimation (soft contact) (*: estimation, - measurement) up: force, down: displacement)

With Fig. 6 the first result is shown. Beside the force estimation also the estimation of the displacement is given. As it can be seen the observer estimation is in good agreement with the measurement itself. On the other side this result is representing the application of a very soft contact. The next experiments are done with stiffer tips. The different tips are characterized by different frequence ranges to be excited. The steel tip is valid up to 8 khz, the medium plastic tip up to 2 khz, the soft tip up to 0.3 khz and the supersoft tip up to 0.2 khz. Fig. 7 shows the comparison between measured and estimated contact forces. For this experiment, the beam has been released from a static deflection to get the initial conditions for free vibrations. The resulting vibrations are measured using the displacement sensor. The model information and the measured displacement is used for the observer reconstructing the contact force. The estimated contact force is compared with an additional measurement of the contact force to validate the observer quality. The given results show that the observer estimates well the displacement (as expected) (cf. Fig. 6 down), and also the contact forces (Fig. 6 up and Fig. 7). For stiffer contacts it is noticed that the observer seems not to be able to reconstruct the dynamic behavior as well as for softer contacts. On the other side it should be mentioned that for this applications the PIO is not tuned.

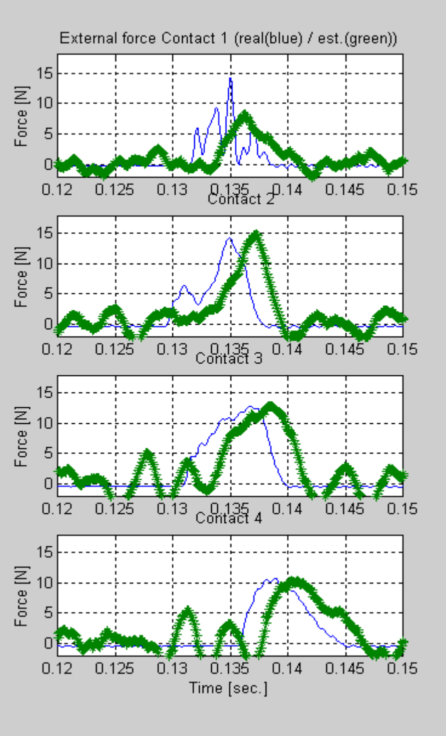

Figure 7. Contact force estimation (top: steel tip, 2. top: medium plastic tip, 3. top: soft tip, bottom: super soft tip; *: estimation, - measurement)

Estimating contact forces acting to a rotating beam

A test-rig has been build up at the Institute of Mechanics at the University of Essen and is strongly related to the research work of Ahrens (Ahrens, 2002), cf. Fig. 8. The testrig is used for model-validating purposes improving the modeling of friction effects between a rubbing turbine blade and the housing of gas turbines for example. A draft scheme of the test rig is given in Fig. 8 right. The test-rig consists mainly of two components, the rotor and the feeding device.The rotor consists of the shaft disc and a small beam device clamped perpendicular to the shaft. The dimension of the shaft disc is choosen in the way that the rotor holds the rotating speed during the rubbing process. The rotor is considered as rigid. The rubbing surface has been mounted on the supporting blade on the front of the carriage. The test blade is screwed into the disc and rubs along the curved rubbing surface once per revolution. The contact forces at the axial and vertical direction are measured by quartz force sensors, which are mounted between the surface and the supporting structure. Here surface strains are measured and the related bendings are calculated (Ahrens, 2002) at two different positions at the clamped blade. The modified strains are used as input signals to the PIO.

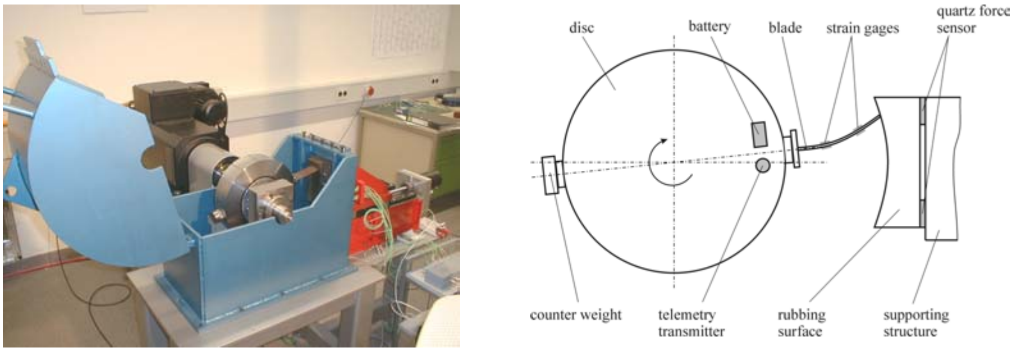

Figure 8. Test rig (University of Essen) and measurement application (Ahrens, 2002)

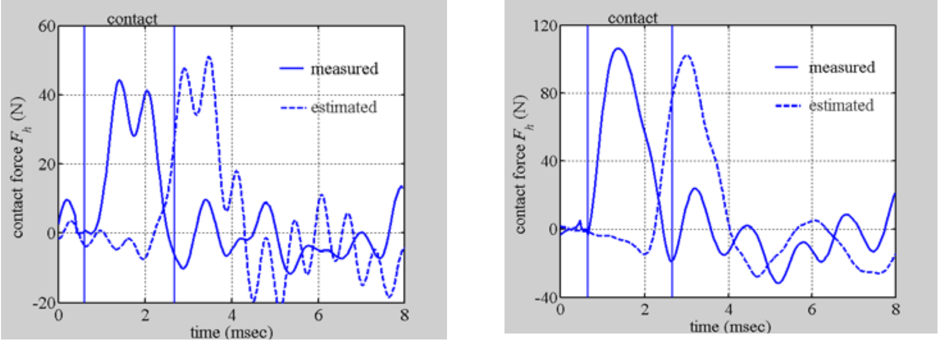

Figure 9. Measured and estimated contact force of the rotating blade (2 measurements) (Ahrens, 2002)

In Figure 9 the results of the application of the PIO to the contact force estimation at the tip of the rubbing blade is given as functions of time. The two figures show the results of two different rubbing processes compared with the vertical measurements of the supporting blade measured directly by the quartz sensors. In both cases the PIO yields a good estimation of the characteristic of the contact force and also of the duration of the rubbing process. One can see that the PIO is also able to reconstruct these high frequency effects.

It should be noted that due to the telemetry transmitter some side effects may occur. This may influence the time characteristic of the signal itself and may also lead to some time delay effects. Due to the clear shape reconstruction of the contact / rubbing process it seems to be obvious, that the time delay is not caused by the observer itself.

If the experiments are repeated using better telemetry support, this aspect will be examined in detail.

Conclusions and Outlook

Initilized by a former joint brazilian-german DAAD-CAPES project some advanced results of model-based contact force estimations are presented. A simple to realize observer technique dealing with an extended state vector containing the estimated unknown effects acting to known dynamical structures is experimentally proved. Therefore a fixed and a rotating beam are used. The contact mechanisms are omitted, the idea of the used Proportional-Observer-Technique is to estimated all external effects as effects acting to known structures. Under some weak conditions (observability etc.) a high-gain approach is used to estimated the forces. Within the experiments the estimations are compared with measured forces. The results show that the technique works well, the observer estimates size, shape and also duration time of the contacts.

Some questions remain and has to be detailed in further examinations: time delay phenomena and observed internal vibrations of the observer, stipulated by the external signals.

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