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MODEL-BASED ESTIMATION OF IMPACT FORCES AFFECTING ELASTIC STRUCTURES: SIMULATION AND EXPERIMENT

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ABSTRACT

The paper introduces into the concept of model-based impact estimation of elastic structures. Based on the model of the affected linear structure a robust linear observer technique is applied to estimate the unknown impacts. The complete procedure of impact estimation is shown by simulations. Results of the observer-based estimation of unknown impacts are presented. As a new result, it is observed that the proposed observer technique can generally (but with limitations) be applied to elastic structures.

INTRODUCTION - THE PROBLEM FROM A MECHATRONIC POINT OF VIEW

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 (Bremer, 1988; Ferreira, 1976; Marghita, 1999; Salm, 1988; Spong, 1989; Ulbrich, 1979). Actual works are focused on flexible (space) structures concerning aspects of practicability/realizability and precision (Cordes, 1992; Hirzinger, 1993). In all these mentioned areas, the classical fields of mechanics/dynamics and control theory as well as data processing are connected. Advanced control approaches usually need some 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.

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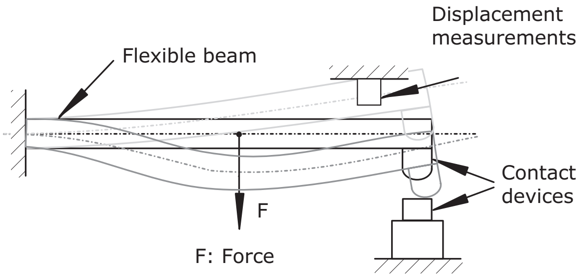

Figure 1. FLEXIBLE BEAM SETUP FOR PRINCIPAL INVESTIGATIONS.

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 (Chen, 1993) applied a nonlinear sliding mode technique to control the motion of a flexible beam and the contact motion.

The advanced 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 (Hollandsworth, 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. Here the PIO-technique is applied to estimate the contact force as well as contact displacements using a minimal number of measurements (one or two sensors) applied beside the contact position. For principal investigations a simply to realize experiment has been done with simulations and experiments. The system to be considered here is shown in Fig. 1. The one-sided clamped elastic beam will be subjected to a load. The resulting movements are restricted due to a contact of the end effector with a contact device. Contact force measurements can be obtained by the use of an impulsehammer as contact device. Along the beam, also strain gages can be applied or displacement measurements can be realized. For principle reasons acceleration measurements are not used. The setup allows to measure both, the contact force directly via the impulsehammer and also the resulting system vibrations at points appart from the impact. The structure thus allows to simulate the problems of the mentioned practical applications (i.e. no direct measurements) but also to take direct measurements at the contact point for comparison.

MODEL-BASED IMPACT ESTIMATION

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). 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 problem is described by

$$\dot{x} = Ax + Bu + Nn(x,u,\mathrm{t}) \quad y = Cx \quad . \tag{1}$$

with the state vector x of order n, the vector of measurements y of order r_1, and the known input vector u of order m. The system matrix A, the input matrix B and the output matrix C are of appropriate dimensions. The unknown effects, which affect the elastic structure are considered with the vector function $n(x,u,\mathrm{t})$ of dimension r_2 and describe in general external inputs here the contact force. In (Söffker, 1999) it is shown, that for this application, the number of independent measurements r_2 must be higher than the number of considered external inputs r_1 (Söffker, 1999).

The input matrix N locates the disturbance to the system description and is assumed as to be known. The structure of the PIO is given in Fig. 2. From the structure it can be seen that the observer feedback is realized by two loops: a proportional (classical) feedback usually used in the Luenberger Observer approach and a second integral feedback introduced in (Söffker, 1995a). The main important applications are realized in (Söffker, 1993; Söffker, 1999). From the structure of the PIO depicted in Fig. 2 it follows, that the dynamics of the PI-observer is described by

$$\dot{\hat{x}} = A\hat{x} + L_3\hat{n} + Bu + L_1(y - \hat{y}) \quad \dot{\hat{n}} = L_2(y - \hat{y}) \tag{2}$$

where $\hat{y} = C\hat{x}$. The integral loop of the PIO is represented by $\hat{n}$. Based on the proof given in (Söffker, 1995a; Söffker, 1999) the observer behavior can be understood in the way, that using high observer gains (due to a special calculation procedure) and also high design values ($L_3 = N$) (with the disturbance input matrix

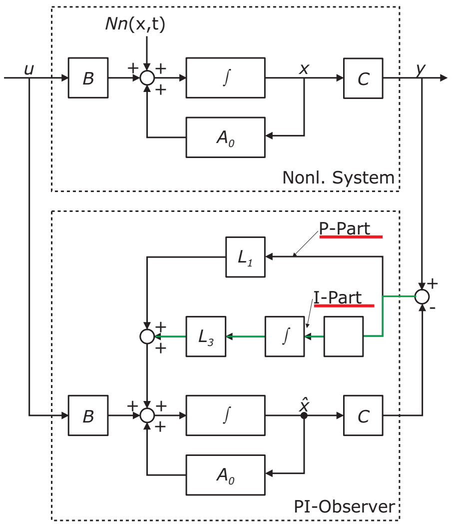

Figure 2. STRUCTURE OF THE PIO.

N) the behavior

$$\hat{x} \to x, \quad \text{and} \quad \hat{n} \to n \tag{3}$$

results. This means that the observer state $\hat{x}$ reconstructs the modeled system state x and the integral feedback of the PIO represents the external disturbance n. The details are given in (Söffker, 1995a; Söffker, 1999). Unfortunately this is not a mathematical constructive proof. Applying a linear disturbance observer technique to a nonlinear problem needs additional explanations:

- The system (Fig. 1) is not considered to be a nonlinear system, but contains a complex contact model.
- The system will be assumed to be a linear system with an unknown force acting on the system. The characteristics of the contact mechanism are assumed to be unknown.
- The assumption of an unknown force acting at a known position onto the linear system allows the application of a linear observer technique, if the observer technique is able to estimate unknown acting effects, cf. (Söffker, 1999).
- The observer-technique to be applied must be able to estimate the modeled states (displacements) and the effect (force).
- If the observer technique gives estimations of the displacement at the contact point and of the interacting force, the contact characteristic can be described (Söffker, 1995b) as a function of these estimated values. In (Söffker, 1999) an actual proof of the convergence behavior is given. The advantages of the proposed Proportional-Integral Observer (PIO) are:
- Estimations of contact displacement and contact force are possible.

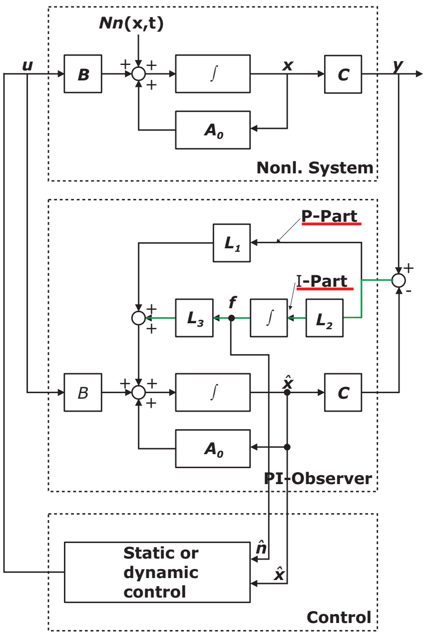

Figure 3. MODEL-BASED CONTROL APPROACH USING PIO-TECHNIQUE.

- For the observer-design the nominal linear model description of the beam can be used.
- For the design procedure itself classical numerical procedures like LQG Design or Pole Placement approaches can be used.

Using the estimations of the PIO, a classical static or dynamic compensation approach can be realized for control purposes. Here, all the estimations of the observer can be used for the calculation of an internal state feedback. The complete structure is illustrated in Fig. 3. The design of disturbance attenuation procedures is well known and will not be given here. Details can be seen in (Müller, 1977).

SIMULATION RESULTS

The system illustrated in Fig. 1 is modeled using 5 finite beam elements. Assuming that the 2 measurements are realized as displacement measurements, the system is elastically deflected by a force acting perpendicular on the beam axis in the way that the gap to the contact device is closed. For first investigations the contact is modeled using a nonlinear stiff spring. The gap between beam and contact is 1mm. The vibrations of the contacting beam can be simulated. The results show that

- the observer technique works well,
- the modeling of the contact behavior gives qualitatively sim-

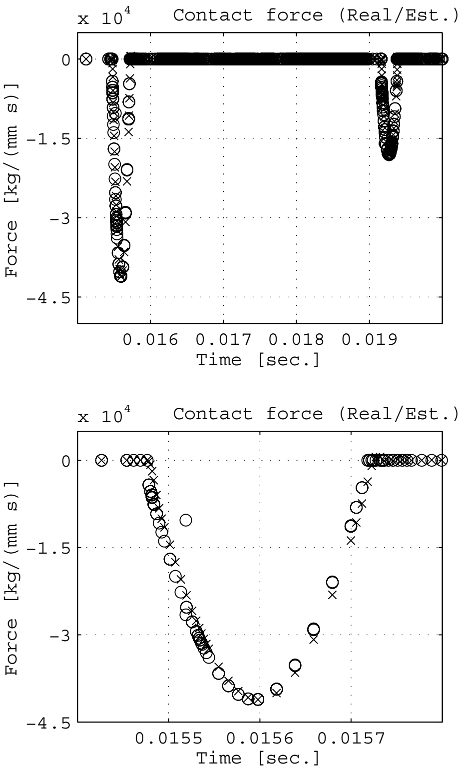

Figure 4. REAL (SIMULATED) AND ESTIMATED CONTACT FORCE, o REAL (SIMULATED), x ESTIMATED.

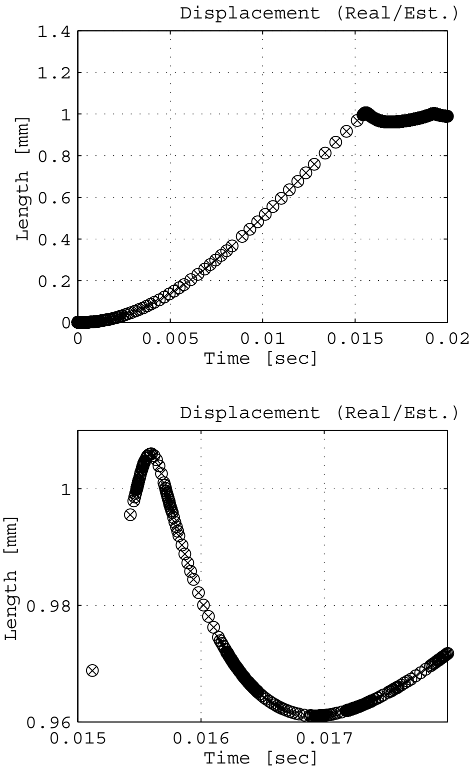

Figure 5. REAL (SIMULATED) AND ESTIMATED CONTACT POINT DISPLACEMENT, o REAL (SIMULATED), x ESTIMATED.

ilar results to those known from the literature, eg. (Yigit, 1995).

Figure 4 illustrates the real (simulated) and the observer-based reconstructed contact force as a function of time. The non-smooth contact and the related impact affecting the elastic structures can be reconstructed using displacement measurements beside the contact (measurements are taken from the nodes between the 2nd and 3rd and the 3rd and 4th beam element. The displacement of the beam contact element is given as simulation and simulated reconstruction in fig. 5. The proposed observer technique is able to estimate contact force as well as contact displacement. The estimations of force and position can be used to reconstruct the contact characteristic. The result is given with fig. 6 (reconstructed contact point stiffness characteristic).

EXPERIMENTAL RESULTS

A test-rig has been built up at the Institute of Mechanics at the University of Essen (Fig. 7). 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. 8 and 10. 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. 9. The measurements have been done at the University of Essen, the application of the PIO to the measurements at the University of Wuppertal. 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. 8 shows the comparison between measured and es-

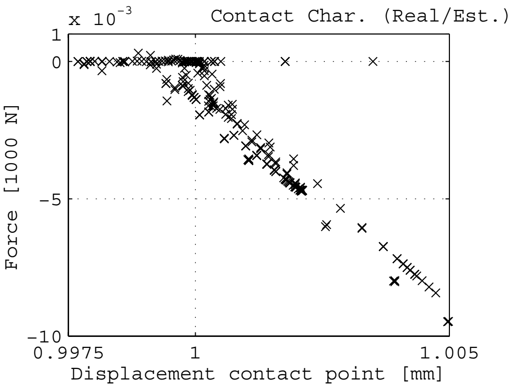

Figure 6. RECONSTRUCTED CONTACT CHARACTERISTIC o REAL (SIMULATED), x ESTIMATED.

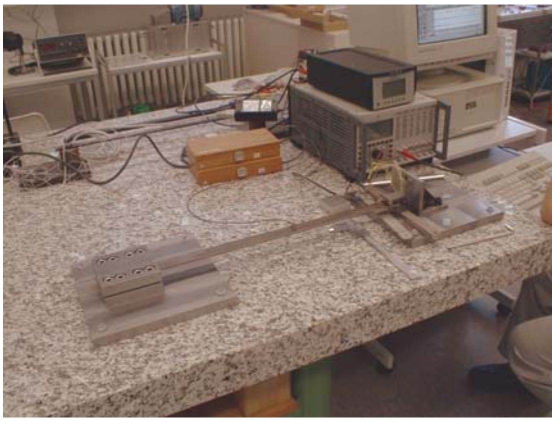

Figure 7. TEST-RIG (INSTITUTE OF MECHANICS, UNIVERSITY OF ESSEN).

timated contact force and also measured and estimated displacement apart from contact point. 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 (Fig. 8 top) to validate the observer quality. The given results show that the observer estimates well the displacement (as expected), and also the contact force. Here the estimation does not fail related to the force peak value and also to the time instant.

The experiments have also been repeated using contact con-

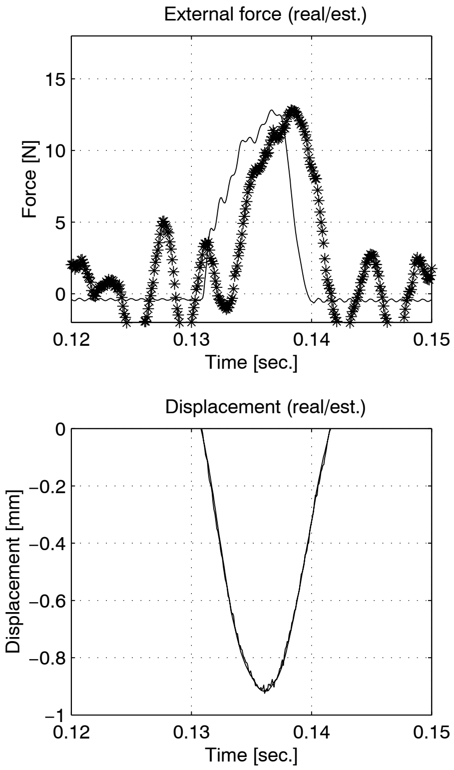

Figure 8. MEASURED AND ESTIMATED CONTACT FORCE (CONTACT POINT), DASH LINE: MEASURED; x: ESTIMATED.

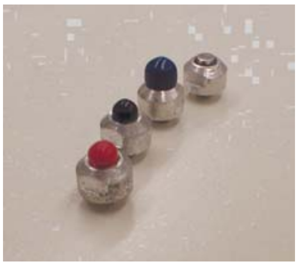

Figure 9. DIFFERENT TIPS OF THE IMPULSEHAMMER USED AS CONTACT (STEEL / PLASTIC (MEDIUM) / SOFT / SUPERSOFT (RIGHT → LEFT)).

ditions leading to longer contact time and smaller contact forces using softer contact tips to validate the observed result. The results concerning the estimation of the contact forces are given in Fig. 10. Here, the observer is able to estimate both, the contact force value as well as the duration time.

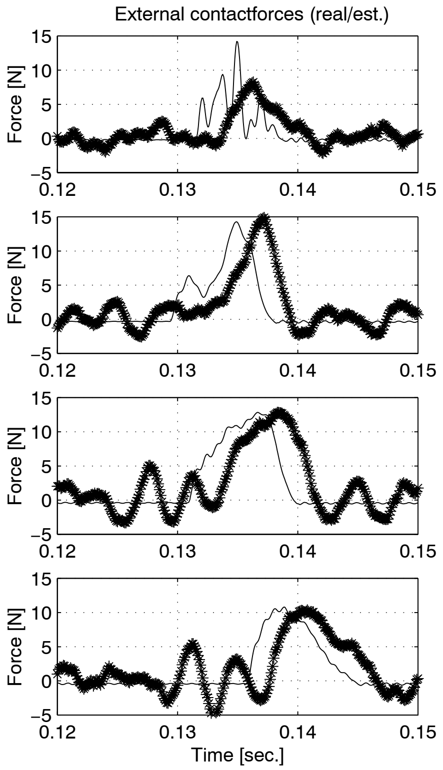

Figure 10. MEASURED AND ESTIMATED CONTACT FORCE (CONTACT POINT), DASH LINE: MEASURED; x: ESTIMATED (CONTACT-MATERIAL: STEEL / PLASTIC / SOFT / SUPERSOFT (Up→Down)).

CONCLUSIONS

The paper introduces into the concept of model-based impact estimation of elastic structures. Based on a robust linear observer technique applied to estimate the unknown impacts, feedback rules can be applied to optimize the dynamical behavior of the system. Simulations show the complete procedure of estimation and give the result that estimations can be realized perfectly. The experimental setup shows the observer-based estimation of unknown impacts affecting the flexible structure. The experimental results demonstrate the application range and the success of the PIO-technique.

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