Modellierung des Mensch-Maschine-Systems für Systemzuverlässigkeitstests: Ermittlung des Anwendereinflusses auf die Belastung der Maschine

Modeling of Human-Machine Systems for System Reliability Testing: Investigation of the User Impact on the Load of the Machine

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Abstract (deutsch): Für die Bewertung der Systemzuverlässigkeit bei Mensch-Maschine-Systeme ist die Kenntnis der Belastung auf das technische System notwendig. Dabei fehlen Simulationsmodelle, welche die Anwenderkräfte bei der Analyse der Systemzuverlässigkeit berücksichtigen.

In dieser Veröffentlichung werden zwei Ansätze zur Ermittlung der durch den Anwender verursachten Belastung auf die Maschine vorgestellt. Der erste Ansatz ist ein Open-Loop-Ansatz, mit dem eine Extraktion in den Kraft-Zeitverläufen möglich wird. Der zweite Ansatz ist ein Closed-Loop-Ansatz, der das Regler-Mensch-Modell als parametrischer, quasilinearer Regler abbildet. Es wird ein Regler-Mensch-Modell aus dem Stand der Forschung eingesetzt und unter Einbezug von experimentellen Daten parametriert.

Die Ergebnisse zeigen den Einfluss des Anwenders auf die Belastungsverteilung der Maschine in der Simulation und die Notwendigkeit zur Berücksichtigung des Menschen im Regelkreis. Durch die Modellierung des Regler-Mensch-Maschine-Systems wird es möglich, mit Hilfe von Simulationen Lastkollektive zu ermitteln, welche die Bewertung der Systemzuverlässigkeit für geänderte Systemparameter und damit unterschiedliche Betriebspunkte zulässt.

Keywords (deutsch):
Mensch-Maschine-System, Systemzuverlässigkeit, Belastungsverteilung, Regler-Mensch-Modell, Lastkollektiv

Abstract (english):

For the evaluation of system reliability in human-machine systems, knowledge of the load on the technical system is necessary. Simulation models for the consideration of user forces in the evaluation of system reliability are missing.

In this publication, two approaches for determining the load on the machine caused by the user are presented. The first approach is an open loop approach, which allows an extraction in the force-time courses. The second approach is a closed loop approach, which models the controller-human model as a parametric quasilinear controller. A controller-human model from the state of the art is used and parameterized with the use of experimental data.

The results show the influence of the user on the load distribution of the machine in the simulation and the necessity to consider the human in the control loop. By modelling the controller-human-machine system it is possible to use simulations to estimate the load collectives. This allows the evaluation of the system reliability for different system parameters and thus different operating points.

Keywords (english):
Human-Machine System, System Reliability, Load Distribution, Control-Human Model, Load Collective

1 Introduction

The reliability analysis of mechatronic products is an important aspect in product development, since the systems are characterized by a high level of complexity (cf. Bertsche et al. 2009). In the quantitative reliability evaluation of a technical system, the failure probability of the subsystems and their interconnection is determined. Starting point of the evaluation are loads, which can lead to damage the components. In addition, the damage mechanisms and the stress tolerance of the components are considered. It is therefore necessary to have knowledge about the load on the particular subsystems. Often these are summarized by experimentally measured load-time courses in load collectives. In order to reduce the time and effort in product development, efficient testing strategies are necessary (see Herzig et al. 2019). Therefore, simulations are used to determine the stress on the components (Bertsche and Lechner 2004; Robert Bosch GmbH 2011; Rieg and Steinhilper 2012).

In human-machine systems, the human behavior influences the reliability of the system, which must be taken into account in the functional and safety evaluations (cp. to VDI 4006 Blatt 1 2015). Thus, it is important that the influence on the load of the human-machine system and its components is appropriate represented. The load on the machine depends on the interaction with the user and the environment.

In the context of the application of handheld power tools - a human-machine system - there is some research on measuring the operating forces between user and machine (hand transmitted force) (see Kalra et al. 2015; Kaulbars 2006; Steffen and Kaulbars 2017; Matthiesen and Uhl 2017; Matthiesen et al. 2015; Uhl et al. 2019), measuring the tool forces resulting from the working process (see Matthiesen and Uhl 2017; Doerr et al. 2019; Matthiesen et al. 2017b) as well as the indirect measurement of the operating forces (Lim et al. 2013; Lim 2014) and load on the machine components (Matthiesen et al. 2016; Matthiesen et al. 2017a). These approaches enables direct or indirect measurement of the external load on the machine or the component load in the application, but the measured load-time courses cannot be transferred to other operating points because the control system *user* is unknown at other operating points. In order to be able to make predictions about the load beyond the experimentally determined operating conditions, models are necessary which allow predictions about the system behavior and the load at other operating points. To ensure this, the human-machine system must be properly modeled, as outlined in VDI-Richtlinie 4006 Blatt 1 (2015) and Havlikova and Sediva (2012).

The interaction with the user can be described for each application by the control loop using the control force and the reaction force. Thus, the control force and the reaction force between user and machine in the control loop are the relevant evaluation parameters that determines in addition with the external forces the load on the machine. While the interactions are system and domain specific for the modeling of the machine, the modeling of the user is done as a controller.

Models for humans as a controller can generally be classified into quasilinear models, optimal theoretical models, as well as nonlinear and adaptive models (Johannsen 1993). Due to the simplicity of the modeling and the acceptable accuracy for the range under investigation, quasi-linear models are commonly used in many investigations. The approximation consists of a linear transfer element with a remnant quantity that is superimposed on the output (Gloeckner 1978; Johannsen 1993; Johannsen et al. 1977). The remnant quantity represents the signal contributions, which cannot be explained by the model. In manual control, there is a distinction between compensatory tracking and pursuit tracking. In pursuit tracking, in addition to the control deviation, both the reference variable and the controlled variable are displayed to the human. In practical situations, there is only a small difference between the two tracking types, especially in the presence of stochastic disturbance variables (Johannsen et al. 1977).

The determination of the transfer functions of human and machine can be carried out by identification procedures using closed or open loop control technology methods of control engineering. Johannsen proposes a transfer function with one zero and two poles as well as a transport delay as basic form of the parametric quasilinear model for the human (Johannsen 1993, p. 234), which we use in the present contribution. The values for the delay time, time constant of muscle delay, delay and lead element are taken from literature, whereby Johannsen (1993) provides a good overview of the ranges.

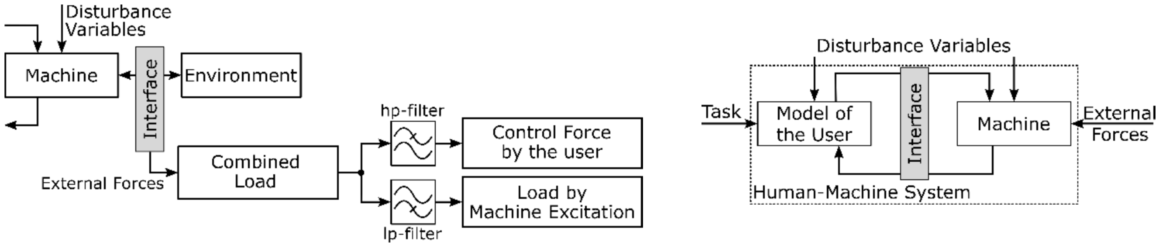
So far as the authors know, in human modelling a control loop has not been used to determine the loads under consideration of user influence, which are the basis of load distribution and load collectives for reliability analysis. There is a lack of simulation models to enable predictions about the human-machine system behavior and the load on the technical system with respect to the operating point. Thus, the research question in this paper is the following:

How can the human-machine system be modelled and simulated with the purpose of predicting the load distribution for system reliability?

Therefore, this paper contributes two approaches: First, a classical open loop approach based on measurement data evaluation to determine the load between machine and environment considering the influence of the user posteriori. Second, a model-based approach to determine the load on the technical system by modelling the human being as a closed loop. The disadvantage of the open loop approach is that the transfer to other operating points is not allowed. For the closed loop approach there is a lack of models which enables the prediction of the load in new operating conditions.

2 Approaches to Modeling the Human-Machine Interaction

To respond to the presented research challenge, we propose two approaches to evaluate the human impact on the mechanical load. The approaches are shown in figure 1. The open loop approach (a) is a kind of measurement data evaluation method. It splits the mechanical load in two parts. The load caused by the machine excitation is extracted by highpass filtering. The load caused by the user is extracted by lowpass filtering. The closed loop approach (b) models the human-machine system as a control loop with a model of the user and the machine. External forces on the machine are considered and the task is used for set point determination. The closed loop approach is implemented as a simulation model.



(a) (b)

Fig 1: Open loop (a) and closed loop approach (b) to evaluate the human impact on the mechanical load.

2.1 Open Loop Approach for Measurement Data Evaluation

In this approach, the load signal y(t) is divided into the signals $y_h(t)$ and $y_m(t)$. The signal processing is shown in figure 2. The signal $y_h(t)$ is the lowpass filtered signal y(t) with the cutoff frequency f_g = 10 Hz and represents the low-frequency control force by the user. The signal $y_m(t)$ is the highpass filtered signal y(t) with the cutoff frequency f_g = 10 Hz and represents the high-frequency excitation force caused by the machine. The low-frequency portion of the exposure results from human exposure and the high-frequency portion of the exposure from machine excitation (see Buxbaum 1972; Radaj and Vormwald 2007). The choose of the cutoff frequency is based on Kern et al. (2009). In this case, the human-induced loads on the machine can be determined. The signal portions can be computated deterministically out of a time signal. For the signal processing, we used a Butterworth filter 5th order. This means a damping rate of about 3 dB at the cutoff frequency and about 100 dB/decade beyond the cutoff frequency.

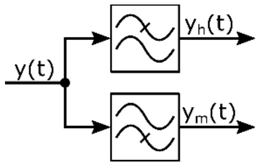


Fig 2: Signal processing of the open loop approach.

2.2 Closed Loop Approach for Simulation Modelling

In this approach, a model of the human-machine control loop is built as shown in figure 3. Note that we use the z-transform for discrete transfer function description. The control-human model consists of the control function $G_c(z)$, $G_h(z)$ and the remnant quantity v(t) based on literature suggestion of Johannsen (1993). The machine model consists a transfer function $G_m(z)$ and the excitation term w(t). The specific parameters for the simulation study described in chapter 3.

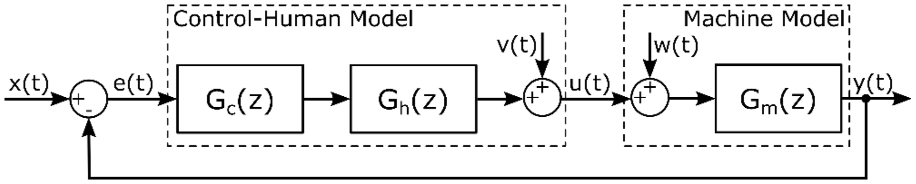
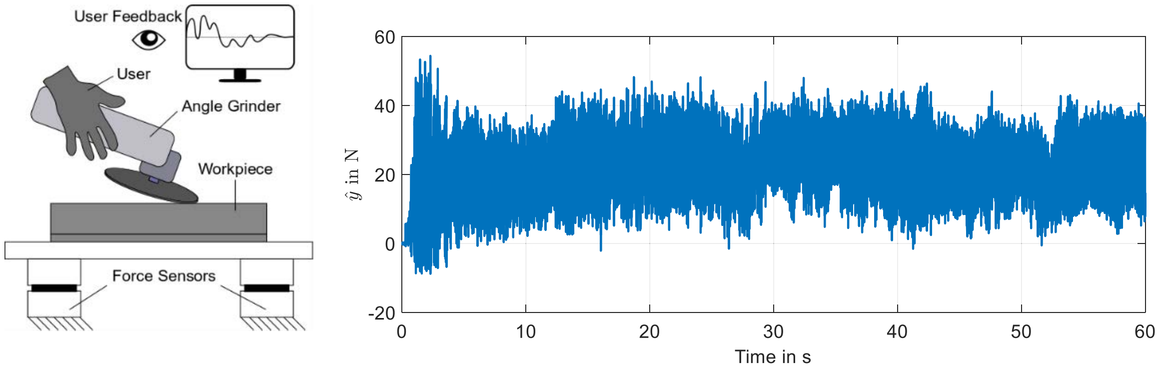


Fig 3: Control loop of the human-machine system.

3 Materials and Methods

3.1 Experimental Data Set

The data set based on an experimental study for roughing metal with a hand-held angle grinder. In the study, a constant pressure force was given to the user and returned to him via a screen. The external forces (tool forces) which applied to the angle grinder were measured using an experimental setup shown in figure 4 (a). For a detailed description of the experimental setup, see Doerr et al. (2019). The results of the experimental study were load-time courses as shown in Fig. 4 (b). The experimental data is used to investigate the two approaches. Note that we use the circumflex to mark the experimental data variable ŷ(t) in contrast to simulated data variables.



(a) (b)

Fig 4: Experimental data set: (a) experimental data setup, (b) time course of the tool force between angle grinder and workpiece, which is measured by the force sensors.

3.2 Simulation Study

A simulation study was carried out and the system behavior was evaluated in the time domain. We assumed the transfer functions $G_c(z)$ with a proportional and integral element as shown in equation 1 and $G_h(z)$ as shown in equation 2. We assumed the remnant quantity v(t) as a random number following normal distribution. The transfer function $G_m(z)$ was derived from experimental data as shown in equation 3 and we defined the function w(t) by a sinusoidal excitation superimposed with a random number following normal distribution. The parameter values were assumed to represent a time course as shown in figure 4. The parameter set was listed in table 1. The label #n describes the parameter set of the simulation run with the according parameter values. The independent variables were the set point of the load and the consideration of the human model. In simulation run #1 and #2 the human model was considered, in simulation run #3 we set $G_h(z) = 1$ and $v(t) = 0$.

Transfer Function $G_c(z)$

$$G_c(z) = \left\{K_\mathrm{h} \frac{K_\mathrm{I} T_s z}{z-1}\right\} \tag{1}$$

Transfer Function $G_h(z)$

$$G_\mathrm{h}(z) = \left\{\frac{8.332^{-05}\mathrm{z} - 8.331^{-05}}{\mathrm{z}^2 - 1.999\,\mathrm{z} + 0.9995}\mathrm{z}^{-6000}\right\} \tag{2}$$

Transfer Function $G_m(z)$

$$G_m(z) = \left\{\frac{0.03928z^{-1} - 0.03872z^{-2}}{1-1.918z^{-1}+0.9191z^{-2}}\right\} \tag{3}$$

Table 1: Parameter of the simulation study

Parameter/ Time course	**Value**		
	Simulation run #1	Simulation run #2	Simulation run #3
x(t)	Step after 1 s to value 25 N	Step after 1 s to value 35 N	Step after 1 s to value 25 N
v(t)	$randn(\sigma^2 = 25, \mu = 0,\ Ts = 1s)$	$randn(\sigma^2 = 25, \mu = 0,\ Ts = 1s)$	0
w(t)	$18\sin(2\pi * 100t) + randn(\sigma^2 = 35, \mu = 0, Ts = 0.005s)$		
K_h	3		
K_I	15		
Ts	5e-5 s		
randn	Random number following normal distribution		

3.3 Data Analysis

The results were evaluated with regard to the load course of the step response and the stress range distribution. For the open loop approach the time course of y_m and y_h is evaluated. The results of the simulation study (closed loop approach) are evaluated for the two step responses (simulation run #1 and #2) as well as for the control loop without human model (simulation run #3) in the time domain. The lowpass filtered signal labeled with a bar. Additionally, the load distribution for the simulation runs is evaluated using the rainflow distribution. The experimental data set $\hat{y}(t)$ serves as reference.

4 Results

In this chapter, the results of the two approaches are presented. The time course of the tool forces and the load distribution was evaluated.

4.1 Open Loop Approach

Figure 5 shows the results of the open loop approach. y_h (t) is shown in the upper part of the figure. At the beginning, the force increases to 15 N within about 1.5 s and rises to 20 N at about 2 s. The force level is kept until 12 s and the target value of 25 N reached. The force quantity y_h (t) varies with a maximum amplitude of about 10 N over the test duration time of 60 s.

The lower part of figure 5 shows y_m(t). The maximum vibration amplitude is about 30 N at the beginning and decreases to a value of about 17 N after rapidly increasing of the mean force.

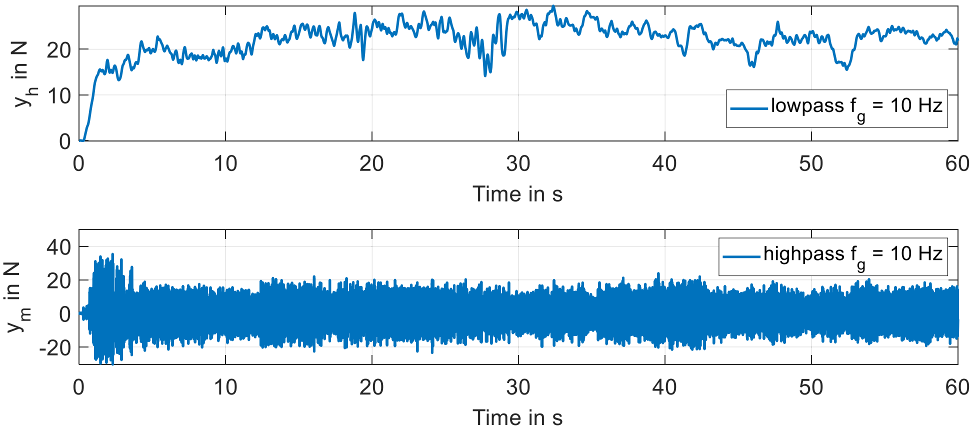


Fig 5: Time courses of the low-frequency control force y_h (t) and high-frequency machine excitation y_m (t).

4.2 Closed Loop Approach

Figure 6 to 8 show the results of the closed loop approach. The step response of the load with a set point value of 25 N in figure 6 shows a ramp response of about 0.7 s to reach the target value. The maximum amplitude of the oscillation is about 25 N. The step response of the load with a set point value of 35 N shows in figure 7 a similar characteristic behavior as in figure 6, where a slight overshoot can be observed.

The time course in figure 8 shows the step response without the human model. The set point value is reached within about 0.6 s. The maximum amplitude of the oscillation is about 5 N and thus significantly smaller than in simulation run #1 and #2.

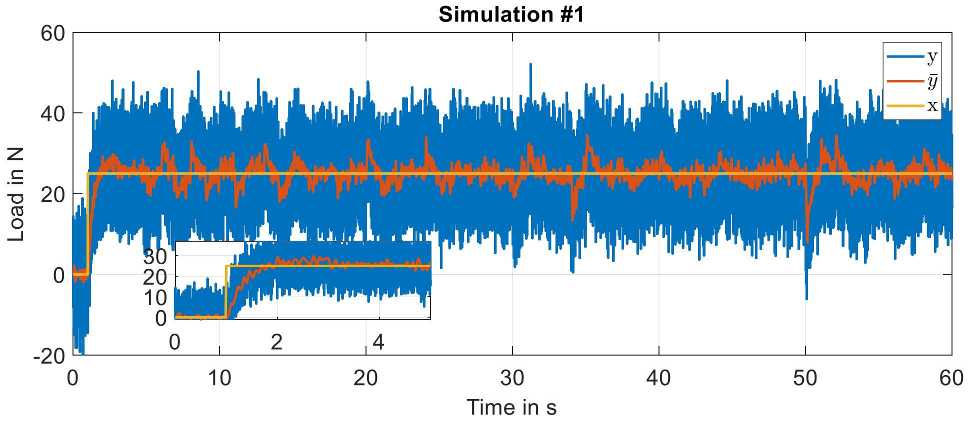


Fig 6: Time course of the load in simulation run #1.

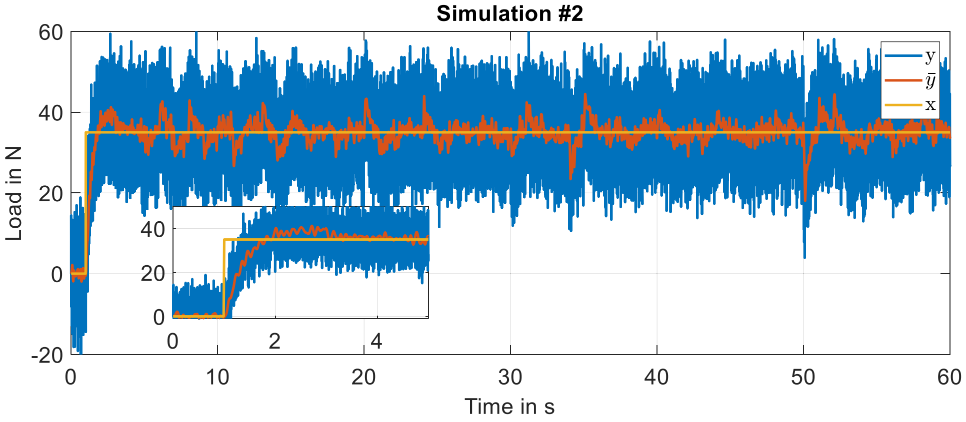


Fig 7: Time course of the load in simulation run #2.

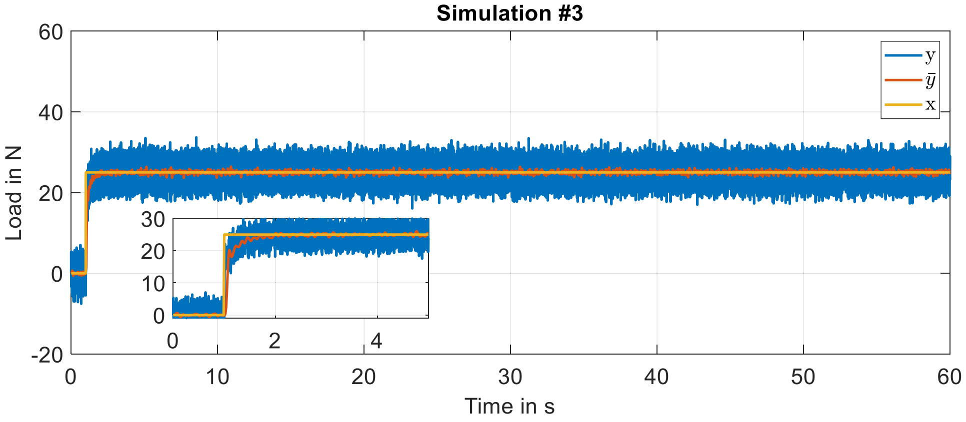


Fig 8: Time course of the load in simulation run #3.

4.3 Evaluation of the Load Distribution for System Reliability Analysis

To evaluate system reliability, the stress range distribution of the load is considered. Figure 9 shows the stress range distribution for the experimental data and simulation run #1 to #3. Simulation run #1 and #2 show a similar distribution as the experimental data, although some deviations could be observed for small load values. The distribution of the stress range is nearly equal for simulation run #1 and #2, only small differences can be observed. The simulation run #3 (without a human model) shows a different behavior in closed loop, both the mean value of the distribution and the number of cycles were much lower.

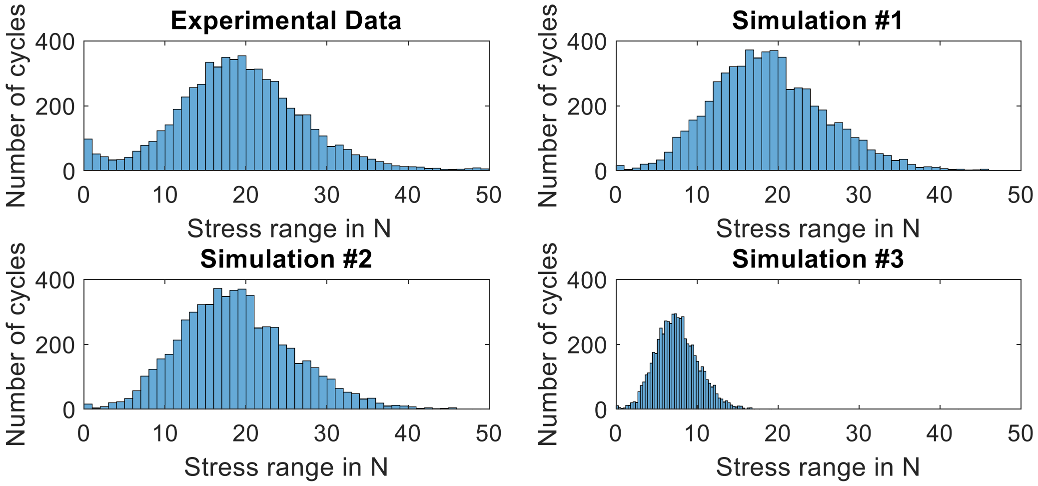


Fig 9: Stress range distribution.

5 Discussion

The open loop approach shows the separation of the load into two parts. One part is influenced by the user and the other part which is determined by the machine excitation. The advantage of this approach is the simple calculation of the load-time data. The disadvantage is that the determined time histories can only be used for the investigated operating points and thus do not allow for variations of the boundary conditions for the analysis of cycle distribution of the load and load collectives.

The closed loop approach makes it possible to consider the human being as a controller in the control loop. The results show comparable load-time data. This is also valid for other operating points, which was evaluated by a different set point. The stress range distribution of the load shows a good match with the experimental data. However, small load amplitudes are significantly reduced in the simulation. Simulation run #3 shows that closed loop modeling is necessary to achieve results comparable to the experimental data.

It must be noted, however, that the analysis of the stress range does not take the mean value of the load into account. Therefore in simulation run #2 the load on the system is higher. Therefore, the distribution is strongly dependent on the machine excitation, since constant operating points were investigated in this contribution. This is particularly relevant for varying operating points. However, the difficulty arises that the target force changes and therefore the traceability of the results is not given. The parameterization of the machine was done by a basic transfer function. It follows that the model of the machine has a limited reproducibility of reality.

The limitations result from the limited investigation of operating points and comparison with experimental data related to these operating points. Furthermore, the parameterization of the controller-human model should be adapted to the investigated human being. The validity of the cycle distribution should be verified by a larger database.

6 Conclusion

In this paper, two approaches to consider the user impact on the load distribution in human-machine systems were presented. While the open loop approach allows a frequency-based evaluation of the forces, the closed loop approach allows the usage of the control-human-machine system for the simulative calculation of load-time courses. The stress range distribution shows a good agreement with the experimental data for the closed loop approach. In the next step, the approaches for evaluating system reliability should be applied and verified in a study.

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