

Stability Analysis of parameter-excited linear Vibration Systems with Time Delay, using the Example of a Sheetfed Offset Printing Press

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This article describes stability studies on parameter-excited linear vibration systems with time delay. A method for stability analysis is presented. Therefore, the transcendental transmission element of the time delay $e^{-s\tau}$ is approximated as an all-pass element with the rational transfer function by means of the so-called Padé approximation. The system can be represented in the state space and the methods of the Floquet theory can also be applied to the system with approximated time delay. The process can be implemented without great effort in a standardized simulation environment such as MATLAB/SIMULINK, whereby existing models and methods can be reused. The suitability of the method is shown in the well-known example of the Mathieu differential equation with time delay. Variations between different solvers and approximation orders are described. An extended view and the transfer to an industrial application take place with the example of the drive of a sheetfed offset printing machine. The relevant vibration system is represented by an oscillator with several degrees of freedom. The belt, which couples the degrees of freedom of the drive motor and the machine, leads to a periodic (harmonic) parameter excitation of the system due to its inhomogeneous nature. The speed and position control of the drive motor (PI controller) is associated with a time delay, resulting in a system of the type described above.

1 Introduction

Sheetfed offset printing machines print individual sheets of paper that are picked up from a pile in the feeder and placed on a pile after they have passed through the machine. At present, production speeds of up to 18,000 sheets/hour (corresponding to 5 sheets/second) can be achieved. The Heidelberg Speedmaster XL162-6 + L is a modern large-format press (sheet format up to 1,210 mm x 1,620 mm) with six printing units and a varnishing unit.

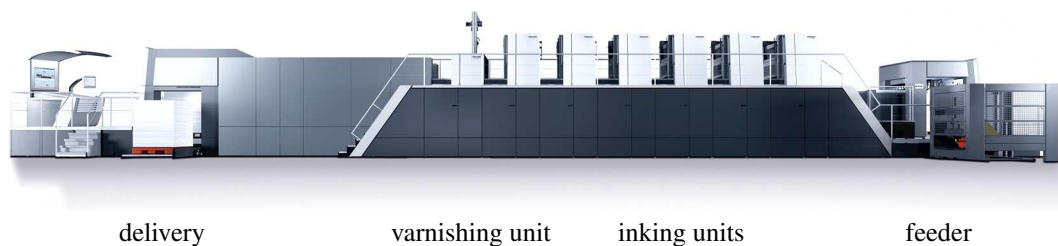


Figure 1: Heidelberg Speedmaster XL162-6 + L sheetfed offset printing press with six inking units and one varnishing unit. The paper sheets pass through the machine from the feeder (right) to the delivery (left).

The hand-over of sheets within the machine takes place by an interconnection of cylinders. The individual cylinders are equipped with grippers which hold the sheet on the cylinder. During the transfer of the sheet from one to the next cylinder, the grippers open and close at defined times. The grippers are controlled by cam drives. All cylinders are coupled by a continuous gear train, which is connected to the electric drive motor by means of a belt drive. The drive control of the machine takes place via a controller with P and I components, which is implemented on a central control unit.

The printing quality is essentially influenced by the position of the individual color separations relative to one another, the so-called register (Kipphan, 2000). Deviations in the position of a few μm result in recognizable color shifts and thus also in a reduction in print quality. Vibrations of the drive train result in relative motions of the

cylinders which then also affect the register. The frequencies and the order of the machine vibrations are also found in the register fluctuation on the sheet.

In operation, the machine is excited by a variety of interfering mechanisms to vibrate. In addition to the reaction moments of the cam mechanisms for the control of the grippers, torque fluctuations from the inking unit, tolerance-related residual moments of the cylinders and moments from the belt drive of the main drive arise. As drive belts, ribbed belts are used, which are constructed from a material composite. Due to manufacturing tolerances, the mechanical parameters of the belt fluctuate over the length of the belt, causing the drive train to vibrate (Langer, 2013; Dresig and Fidlin, 2013). With respect to printing machines, such vibrations were examined by Messer (2012). Furthermore, it is known from the experience that in many cases the time delay in the control units can not be neglected. The time delay has an effect on the machine vibrations such as negative damping.

In order to gain a better understanding of the acting effects as a result of excitation by the belt drive, a model is built, which makes it possible to study the machine vibrations including the parametric system excitation and time delay. This article focuses on the stability analysis of the system. The modeling and evaluation are realized in the program environment of MATLAB/SIMULINK.

The investigations are carried out on a sheetfed offset printing machine Heidelberg Speedmaster XL162-6 + L, as shown in Fig. 1.

2 Basic System Modeling

Mechanical systems, whose descriptive parameters are time-dependent, are important in many technical applications. The fluctuations in the mechanical parameters of the drive belt described in the previous section can also be modeled by time-dependent system coefficients (see also Messer (2012) or Dresig and Holzweißig (2011)). Further examples of this can be found in the case of unevenly translated mechanisms, rotors, gear transmissions, and other fast-running traction drives (Dresig and Holzweißig, 2011; Dresig and Fidlin, 2013). In the present case of the main drive of a sheetfed offset printing press, preliminary investigations were presented in Messer (2012).

As part of the heteronomous vibrational systems, systems with time-dependent coefficients are referred to as parameter-excited or rheonomous systems (Deutsches Institut für Normung e.V., 2000). They can be represented in their general form as a $2N$ -dimensional Ordinary Differential Equation (ODE) system with time-dependent coefficients

$$\dot{\mathbf{y}}(t) = \mathbf{A}(t)\mathbf{y}(t). \quad (1)$$

Hierin, $\mathbf{A}(t) \in \mathbb{R}^{2N \times 2N}$ is the system matrix and $\mathbf{y}(t) \in \mathbb{R}^{2N}$ the state vector.

By means of an additional time delay τ , occurring for example, in the case of closed-loop systems for which the time delay in the information processing system can not be neglected, Eq. (1) expands with the system matrix $\mathbf{B}(t) \in \mathbb{R}^{2N \times 2N}$ to

$$\dot{\mathbf{y}}(t) = \mathbf{A}(t)\mathbf{y}(t) + \mathbf{B}(t)\mathbf{y}(t - \tau). \quad (2)$$

Systems with time delay are represented by Delayed Differential Equations (DDE). In the case of an assumed periodic time dependency, it also holds that

$$\mathbf{A}(t) = \mathbf{A}(t + T) \quad \text{and} \quad \mathbf{B}(t) = \mathbf{B}(t + T). \quad (3)$$

The investigation of the stability is an important point in the study of the above mentioned applications. In the case of heteronomous ODEs, as occur in the mechanical systems mentioned, the parameter excitation can cause the system to have destabilizing resonances (e.g. Dohnal (2012); Dresig and Holzweißig (2011) or Gasch and Knothe (1989)). They can be calculated according to

$$\omega_n^{k,l} = \frac{|\omega_k \pm \omega_l|}{n}, \quad k, l = 1, 2, \dots \quad (4)$$

Here, ω_k and ω_l denote the k th and l th eigenfrequencies of the time invariant system, and n the order of the

resonance. It is called parameter resonance for $k = l$ and of parameter combination resonances for $k \neq l$.

In the case of autonomous DDEs as they can be found for example in controlled systems, the time delay results in a phase shift, which increases continuously with increasing frequency and can cause instability (Lunze, 2012).

3 Stability Analysis Methods

The stability studies of parameter-excited systems without a time delay Eq.(1), ie of heteronomous ODEs, can be carried out with the help of the so-called Floquet theory (see, e.g. Dohnal (2012); Gasch and Knothe (1989) or Tagawa (1967)). Based on a set of $2N$ linearly independent initial conditions $\mathbf{y}(0)_1, \mathbf{y}(0)_2, \dots, \mathbf{y}(0)_{2N}$, the monodromy matrix $\Phi(T, t_0 = 0)$ is obtained by numerical integration of the system equations (1) over the period T . Based on the eigenvalues μ_n of the monodromy matrix, the stability of the system can be carried out. The system is asymptotically stable if all $2N$ eigenvalues of the monodromy matrix are less than one in amount, and thus lie inside the unit circle in the complex plane.

For autonomous DDEs, see Eq. (2) with $(\mathbf{A}(t), \mathbf{B}(t)) = (\mathbf{A}_0, \mathbf{B}_0)(\text{const})$, the stability statement can be made in analogy to autonomous ODEs, see Eq. (1) with $\mathbf{A}(t) = \mathbf{A}_0(\text{const})$, by means of the eigenvalues of the characteristic equation (Gu and Niculescu, 2003; Wu et al., 2010). The stability is asymptotically given if all eigenvalues λ_n have a negative real part and thus lie in the left half-plane of the complex plane. In contrast to autonomous ODEs, for autonomous DDEs, the characteristic equation $\det(\lambda \mathbf{I} - \mathbf{A}_0 - \mathbf{B}_0 e^{-\lambda\tau})$ is a transcendental equation, which has an infinite number of solutions because of the term $e^{-\lambda\tau}$. For a numerical stability analysis, it is necessary to find a suitable approximation for $e^{-\lambda\tau}$ to obtain a finite number of solutions. Thus, in control engineering, rational functions are often used (Lunze, 2012). One possible way to get a suitable model is the so-called Padé approximation (see, e.g. Lam and Chung (1992); Lam (1996); Baratchart et al. (1995)). In Gu and Niculescu (2003), a comprehensive overview of further procedures and the handling of time delay in the context of stability considerations and the control of systems is given (see also Sipahi and Olgac (2006); Sipahi et al. (2011) or Wu et al. (2010)). The functionalities that MATLAB offers in handling systems with time delays are explained in Gumussoy et al. (2012).

In the case of heteronomous DDEs the Floquet theory can be extended, the result is a monodromy operator of infinite dimension (Insperger and Stépán, 2003; Tweten et al., 2012). The stability of heteronomous DDEs can be determined by various highly efficient discretization methods, which have been developed in recent years. The general objective of the discretization methods is to approximate the monodromy operator of infinite dimension by a monodromy matrix of finite dimensions. The semi-discretization method develops the DDE into a system of piecewise autonomous ODE (Insperger and Stépán, 2002a, 2004; Insperger et al., 2004). The so-called temporal finite element method and, in particular, the transition to the so-called spectral element method are presented in Khasawneh and Mann (2011), see also (Khasawneh et al., 2010; Tweten et al., 2012; Ahsan et al., 2015a) or (Ahsan et al., 2015b). While the temporal finite element method is a piecewise approximation of the DDE that has the full flexibility of a spatial finite element method, the so-called collocation method is a global approximation over the DDE domain (Khasawneh et al., 2010), see also (Khasawneh and Mann, 2011; Tweten et al., 2012; Butcher and Bobrenkov, 2009) or (Breda et al., 2015).

The described methods for the stability analysis of heteronomous DDEs are numerically highly efficient, but they are also complex and usually only to be implemented with some effort in an existing methodology. In the industrial context it is necessary to use standardized methods and simulation environments. MATLAB/SIMULINK is such a simulation environment. There is the possibility to model systems by graphical blocks. MATLAB/SIMULINK is used in particular for time domain simulation and for controller design. If a mechanical system and its controller is already modeled in MATLAB/SIMULINK, it is desirable to be able to carry out further investigations, such as the stability analysis, also in this simulation environment. For this reason, a method for stability analysis on heteronomous DDEs is presented in this thesis, which can be integrated into the existing methodology under MATLAB/SIMULINK without much effort.

In the method described here, the time delay is approximated by a rational function (see also (Lunze, 2012)). Thus the heteronomous DDE (2) becomes a heteronomous ODE

$$\dot{\mathbf{y}}(t) = \mathbf{A}(t)\mathbf{y}(t) + \mathbf{B}(t)\mathbf{C}_0\mathbf{y}(t), \quad (5)$$

where the approximated properties of the time delay are represented by \mathbf{C}_0 . The dimension of the system increases as a result of the approximation in Eq. (1) or Eq. (2). The stability of the so approximated system can then be

determined for various parameter combinations according to the above-described Floquet theory.

The so-called Padé approximation is a common method for obtaining a suitable approximation of the propagation delay (see, e.g. Lam and Chung (1992); Lam (1996); Baratchart et al. (1995)). By applying the Laplace transformation, the time delayed function $\mathbf{y}(t - \tau)$ can be converted into the frequency domain

$$\mathcal{L}\{\mathbf{y}(t - \tau)\} = \mathbf{Y}(s) e^{-s\tau}. \quad (6)$$

The aim of the approach is the approximation of the transcendental element $e^{-s\tau}$ by a rational function of the type

$$R_{K,L}(s\tau) = P_{K,L}(s\tau)/Q_{K,L}(s\tau), \quad \text{with} \quad \deg P_{K,L} = K, \quad \deg Q_{K,L} = L. \quad (7)$$

This is a Padé approximation of the type (K,L) . According to e.g. Baratchart et al. (1995), explicit formulations are available for the numerator polynomial $P_{K,L}(s\tau)$ and the denominator polynomial $Q_{K,L}(s\tau)$ with

$$P_{K,L}(s\tau) = \sum_{m=0}^K \frac{(K+L-m)! K!}{(K+L)! m! (K-m)!} (-s\tau)^m, \quad Q_{K,L}(s\tau) = \sum_{m=0}^L \frac{(K+L-m)! L!}{(K+L)! m! (L-m)!} (s\tau)^m. \quad (8)$$

If the time delay is approximated in this way, Eq. (5) has the dimension $2N + L$ and the above-described steps can be applied to perform the stability study on heteronomous ODE according to the Floquet theory. The monodromy matrix $\Phi(T, t_0 = 0)$ returns $2N + L$ eigenvalues μ_n , by which the stability statement is made. This approach can also be found in Tagawa (1967).

The described method is implemented in MATLAB/SIMULINK. In order to prove its suitability, stability studies are carried out on a known example, the delayed Mathieu differential equation. Furthermore, various numerical solvers and approximation orders are examined.

As a further application example, the transfer to the sheetfed offset printing machine Heidelberg Speedmaster XL162-6 + L described in section 1 is carried out. The influence of various parameters, which in particular concern the control of the machine, is investigated.

4 Examples

4.1 Delayed Mathieu Differential Equation

The delayed Mathieu differential equation is one of the simplest equations, which maps the two properties of the parameter excitation and the time delay, and still has a practical relevance (Stépan and Insperger, 2006)

$$\ddot{q}(t) + a_1 \dot{q}(t) + (a_2 + a_3 \cos(\Omega t)) q(t) = b q(t - \tau). \quad (9)$$

This differential equation can be interpreted as the system equation of a mechanical oscillator with one degree of freedom and position control.

On the left side of this DDE are the system parameters; a_1 is the damping and a_2 and a_3 are the mean value and the amplitude of the harmonic stiffness, respectively. On the right is the controller parameter b , which amplifies the τ delayed signal. For various combinations of the coefficients a_1 , a_2 , a_3 and b , there are analytical and numerical solutions in the literature. Therefore, this example is excellent for verifying the applicability of the method described in section 3.

4.1.1 System with Parameter Excitation, without Time Delay ($a_3 \neq 0, b = 0$) (heteronomous ODE)

The stability map of Eq. (9) with $b = 0$ has been calculated for the first time by Strutt and Ince. Representations can be found, for example, in Insperger and Stépan (2002b); Magnus and Popp (1997) or Klotter (1978), where Klotter (1978) as well as Magnus and Popp (1997) provide detailed technical discussions.

The following Fig. 2 shows the computed stability map, stable areas are marked 'S' herein.

Since the system (9) does not have a delay time with $b = 0$, a Padé approximation is not performed. The MATLAB/SIMULINK block to approximate the time delay is a constant of the magnitude one after Eq. (7) and Eq. (8).

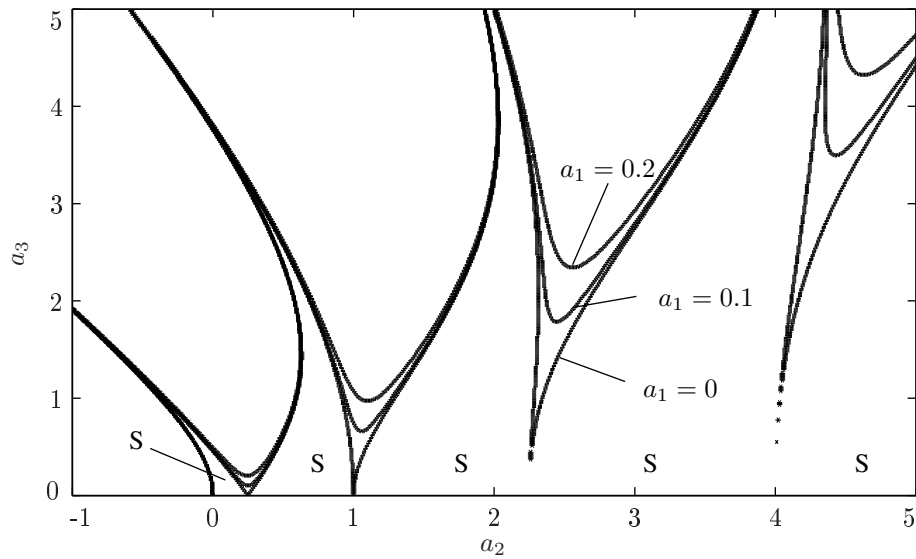


Figure 2: Stability map in the (a_2, a_3) -plane with $b = 0$ for $\Omega = 1$, $\tau = 2\pi$, Padé type $(0, 0)$, solver ode23tb.

The accordance of the results shown in Fig. 2 with those found in the literature (Inspurger and Stépán (2002b); Magnus and Popp (1997) or Klotter (1978)) is good. Only the narrow slopes of the unstable areas at $a_2 = 2.25$ and $a_2 = 4$ are not found through to the abscissa.

Since the stability maps are determined by numerical integration, the quality of the result is partly dependent on the solver used. MATLAB/SIMULINK offers two classes of solvers, with constant step size and with variable step size. Compared with constant-step solvers, variable-step equilibrators provide greater stability, whereas the cost per unit of time to be calculated is usually greater (The Mathworks, Inc., 2008). Fig. 3 shows a comparison of a section of the stability map shown in Fig. 2 for various solvers.

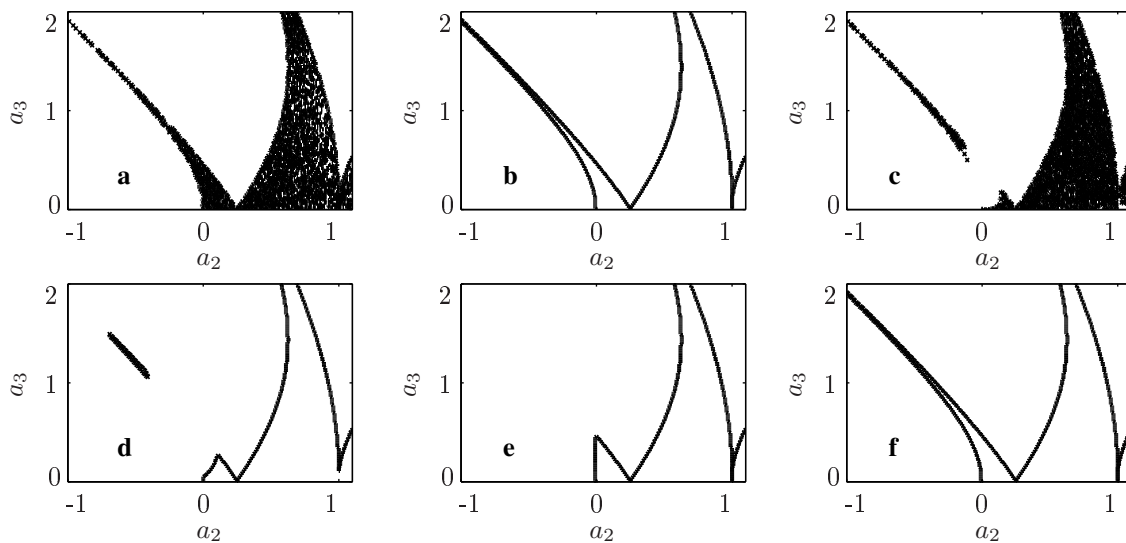


Figure 3: Stability map in the (a_2, a_3) -plane with $b = 0$ for $\Omega = 1$, $\tau = 2\pi$, Padé type $(0, 0)$, solver: **a)** ode45, **b)** ode23, **c)** ode113, **d)** ode15s, **e)** ode23t, **f)** ode23tb.

There are clear differences in the results shown in Fig. 3. The solvers ode23 and ode23tb provide the best results

as can be seen clearly. The maximum time step, which the solver is limited to, also has a strong influence on the quality of the results. A reduction of the maximum time step leads to better results, an increase to poorer results. The results shown in Fig. 3 are generated with a maximum time step size of $5 \cdot 10^{-4} T$, where T is the cycle time. Since the solvers ode23 and ode23tb perform equally well, with respect to robustness of results against higher time steps and computational time, and both provide slight numerical damping, the decision is arbitrary. Therefore, the simulations are performed using the equation solver ode23tb. The special features of the individual solvers can be found in the MATLAB/SIMULINK help (The Mathworks, Inc., 2008).

4.1.2 System without Parameter Excitation, with Time Delay ($a_3 = 0, b \neq 0$) (autonomous DDE)

An autonomous oscillator with time delay follows from Eq. (9) if $a_3 = 0$ is set. In this case, the stability map is shown in the (a_2, b) -plane. For an undamped oscillator with $a_1 = 0$, there is an analytical solution after Insperger and Stépán (2002b). The boundary curves of the stability map are straight lines that have the slope ± 1 for $\Omega = 1$ and $\tau = 2\pi$. They intersect the abscissa in the points $(p/2)^2$, ($p = 1, 2, \dots$).

The numerical solution according to the described method with a Padé approximation of the time delay of the type (10, 10) is shown in Fig. 4.

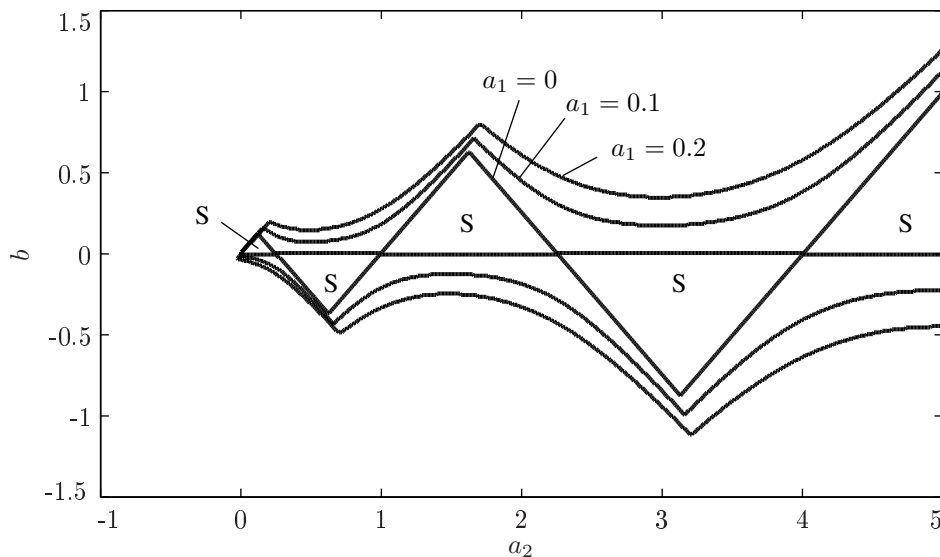


Figure 4: Stability map in the (a_2, b) -plane with $a_3 = 0$ for $\Omega = 1, \tau = 2\pi$, Padé type (10, 10), solver ode23tb.

The stability map in the (a_2, b) -plane clearly shows the described properties of the analytical solution for $a_1 = 0$. The boundary curves with the slope ± 1 intersect the abscissa as mentioned in the points $(p/2)^2$, ($p = 1, 2, \dots$), see also the solution in the (a_2, a_3) -plane (Fig. 2).

The quality of the approach of approximating the transcendental function $e^{-s\tau}$ with the Padé approximation, described by Eq. (8) and Eq. (7), is strongly dependent on the order of the approximation, i.e. the type. For this example, the Padé approximations converge from type (10, 10), see also Fig. 5.

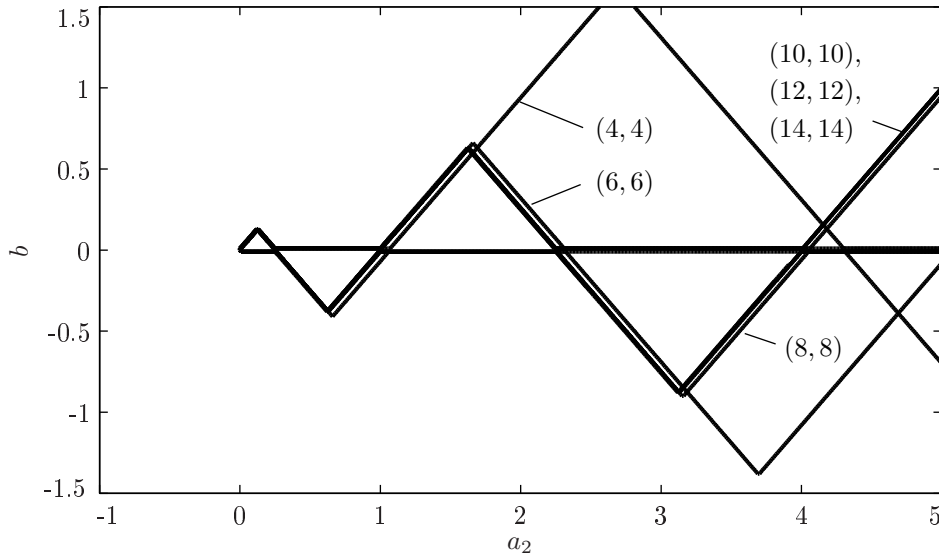


Figure 5: Stability map in the (a_2, b) -plane with $a_3 = 0$ for $\Omega = 1$, $\tau = 2\pi$, Padé type see marking, solver ode23tb.

4.1.3 System with Parameter Excitation, with Time Delay ($a_3 \neq 0$, $b \neq 0$) (heteronomous DDE)

The generalization or the combination of the two previous cases represents the solution of the heteronomous DDE. Therefore, both parameters a_3 and b are not equal to zero. In Fig. 6 the solutions for various values a_3 are shown in the (a_2, b) -plane. Again, the consistency with already published data is very good (e.g. Insperger and Stépán (2003)).

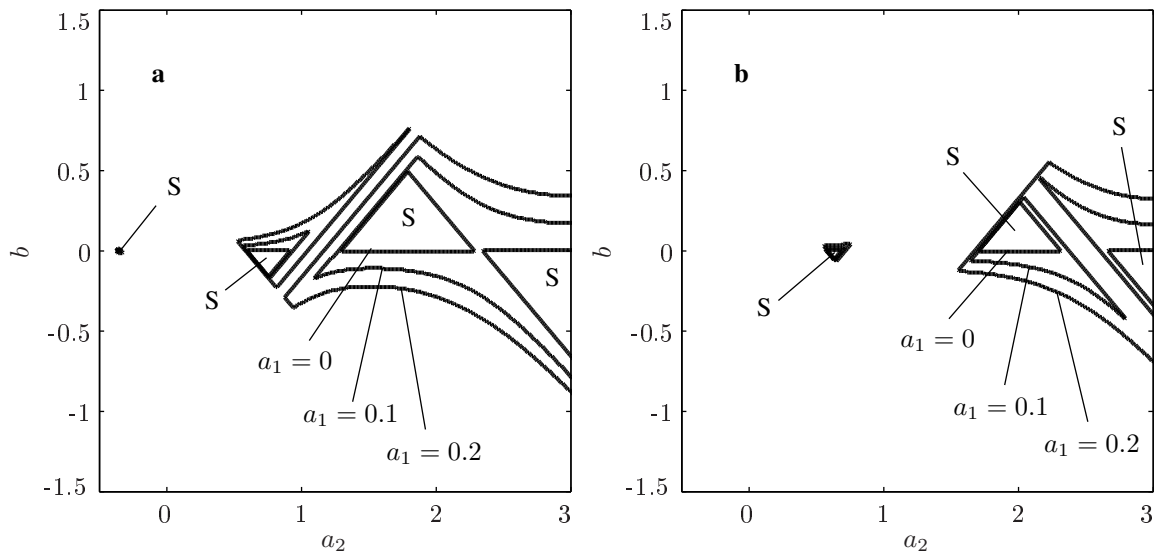


Figure 6: Stability map in the (a_2, b) -plane with **a)** $a_3 = 1$, **b)** $a_3 = 2$ for $\Omega = 1$, $\tau = 2\pi$, Padé type (10, 10), solver ode23tb.

For all of the cases described above, the data obtained with the described method very well agree with known and published data. The approach of approximating the transcendental function $e^{-s\tau}$ with a rational function, the so-called Padé approximation, can thus be applied to convert a heteronomous DDE into a heteronomous ODE. The stability of this heteronomous ODE can then determined by applying the Floquet theory. The procedure can easily

be integrated into the simulation environment of MATLAB/SIMULINK and thus represents a process that can be implemented in an industrial context.

4.2 Sheetfed Offset Printing Machine (system with N degrees of freedom)

The actual focus of the investigations is, as described above, on the stability analysis of the drive of the Heidelberg Speedmaster XL162-6 + L sheetfed offset printing press. This is a sheetfed offset printing machine with six printing units and a varnishing unit. In the course of modeling, the MATLAB/SIMULINK model of the actual printing press is reduced to an oscillator with two modal degrees of freedom, ie the rigid-body mode and the first flexible mode, and then coupled to the drive. The system equation

$$\mathbf{M}_S \ddot{\mathbf{q}}(t) + \mathbf{D}_S \dot{\mathbf{q}}(t) + (\mathbf{K}_S + \epsilon \cos(\Omega_{PE} t) \mathbf{K}_{PE}) \mathbf{q}(t) = \mathbf{G}_I \dot{\mathbf{q}}(t - \tau) + \mathbf{G}_P \mathbf{q}(t - \tau) \quad (10)$$

contains with \mathbf{M}_S , \mathbf{D}_S and \mathbf{K}_S the mass, damping and stiffness matrices of the mechanical system. In addition, $\epsilon \cos(\Omega_{PE} t) \mathbf{K}_{PE}$ describes the parameter excitation and $\mathbf{G}_I \dot{\mathbf{q}}(t - \tau) + \mathbf{G}_P \mathbf{q}(t - \tau)$ is the time delayed speed and position control. For the parameter excitation \mathbf{K}_{PE} is the stiffness matrix of the drive belt and $\epsilon \cos(\Omega_{PE} t)$ describes the harmonic oscillation of the belt stiffness. For the control matrices, it is furthermore limited that they are composed of scalar gain factors g_I and g_P as well as coupling matrices \mathbf{T}_I and \mathbf{T}_P which contain only zeros and ones

$$\mathbf{G}_I = g_I \mathbf{T}_I, \quad \mathbf{G}_P = g_P \mathbf{T}_P. \quad (11)$$

Eq. (10) can be easily converted into Eq. (2) and by applying the Padé approximation it can be converted further into Eq. (5).

The result of the stability consideration by varying the machine speed ν and the relative variation of the belt stiffness ϵ for various gains of the speed control g_I and time delays τ is shown in Fig. 7.

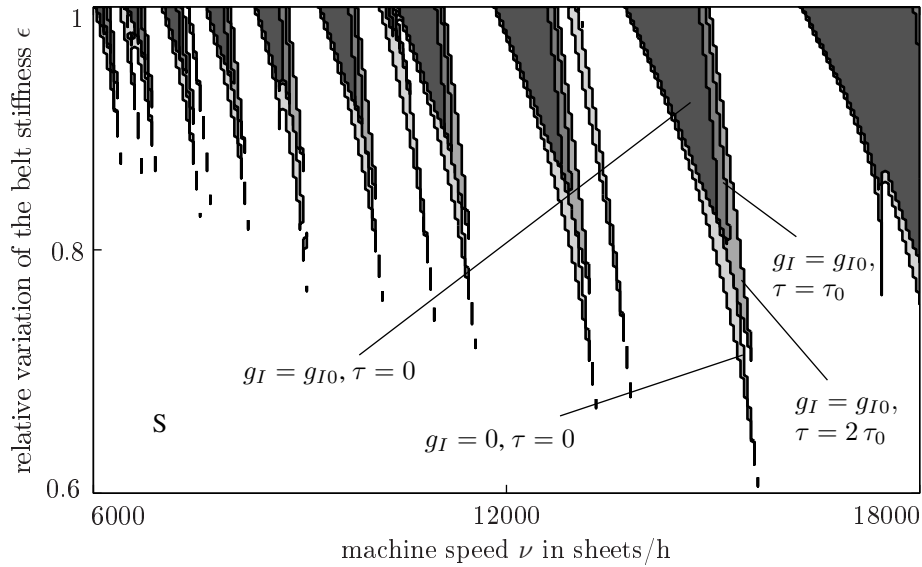


Figure 7: Stability map in the (ν, ϵ) -plane with $\Omega_{PE} = \Omega_{PE0}$, $g_p = g_{p0}$, $\tau = \tau_0$, Padé type (10, 10), solver ode23tb.

It can be seen that the system can be stabilized by the additional damping due to the speed-proportional regulation. The system with $g_I = 0$ and $\tau = 0$ serves as a reference. The time delay principally acts as a negative damping, which can be clearly seen by the increase in the unstable ranges as a result of an increasing time delay. Furthermore, the time delay still shows a different effect, the unstable areas are slightly shifted towards the higher machine speeds compared to the reference system. Overall, it can also be seen that instability occurs only at very large amplitudes of the parameter excitation ($\epsilon > 0.6$).

5 Summary and Conclusions

In this thesis, a method has been proposed which allows heteronomous DDEs to be converted into heteronomous ODEs via the Padé approximation. The heteronomous ODEs can be modeled without great effort in a standardized simulation environment such as MATLAB/SIMULINK. Using the Floquet theory, the stability maps can be calculated by numerical integration of the system equations. The suitability of the method was shown in the well-known example of the delayed Mathieu differential equation. Differences and influences of various solvers and approximation orders were investigated and illustrated. Finally, the transfer of the method to a practical example was carried out and the stability behavior of a sheetfed offset printing press was examined. The tests were carried out as a function of the machine speed and the relative variation of the stiffness of the drive belt for various system configurations. It is shown that time delay increases the unstable areas of the stability map because it has the effect of a negative damping.

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