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Strategies to evaluate musculoskeletal disorders to the human arm hand system using similarity metrics

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Abstract

The study of the behavior of the hand-arm system can present quantitative knowledge through the overall A(8) daily vibration exposure with the possibility of establishing significant properties of the state and output of the hand-arm system. The present research proposes the qualitative and quantitative analysis of the asymptotic behavior of the arm system by Popov's theorem. The hand-arm system consists of subsystems, such as the operator's fingers, wrist, elbow, and shoulder. The back offers a support structure to the arm-hand system. Using Popov's theorem, the study of stability allows the evaluation of the stability of the individual subsystems in the presence of vibrations.

1 Introduction

Back pain depends on the mechanical vibrations generated by the tools utilized during manual labor. These vibrations, which can be excessive and prolonged, can impose stress on both the entire body (WBV) and the hand–arm system (HAV). Over time, this can result in various health issues. In particular, an individual may experience pain in the hands and lower arms, back pain, and challenges related to lumbar disc herniation (Cavacece (2021)). Mechanical shocks on the whole body and hand–arm system characterize the activities of manual workers. Low back pain risk factors are posture and stress induced by electro-mechanical tools. In their daily work, a worker with manual skills can use one or more devices that can produce mechanical vibrations, such as the following portable power tools: brush cutter, chainsaw, and electric saw (Fattorini et al. (2017)). A brush cutter's mechanical vibration emissions can generate a professional risk of mechanical vibration injury, which stresses the human body. Frequent exposure to whole–body vibration and hand–arm systems can deteriorate human body capabilities even with permanent effects (Cavacece et al. (2005)). The tools are designed and engineered to minimize exposure to the human hand, with careful consideration given to their use and occupational management. While operators may not be vibration control specialists, they will want to reduce hand-arm vibration levels or improve comfort and may seek cost-effective ways. However, it is unlikely that they will consider all of the relevant factors when making improvised modifications or interventions on the hand-arm system. The arm hand system presents an interaction with the human spine and in relation to other parts of the human body. The spine acts as the main support structure for the upper body, protecting against spinal ailments that could have serious neurological consequences. These ailments frequently result from exposure to vibrations, working postures, physical exertion, physical attributes,

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noise levels, and individual susceptibility to pre-existing conditions or age. The intervertebral discs are vital in supporting high levels of compressive loads and shear deformations, allowing for flexibility and rotation. The dose–response model considers the vibration exposure of the hand-arm system and other symptoms associated with hand–arm vibration syndrome (HAVS). Factors such as the direction of transmission, grip strength, stress, skill, type of tool grip, and individual susceptibility are all considered within this model, including exposure patterns. Numerous instruments are crafted from metal, a superb thermal conductor that can transmit heat or cold to the touch. Incorporating a casing may offer the added benefit of insulation against the cold. Research on hand-arm vibration has revealed a correlation between cold exposure and the worsening or onset of HAVS. Placing a foam envelope between your hand and the tool can increase friction and reduce the effort required to handle the tool properly. The foam envelope, in turn, can help reduce stress and lower the risk of hand-arm vibration transmission. It's important to note that the tool handle plays a crucial role in this process, as its shape, size, and orientation can all impact how the handle affects your hand–arm vibration transmission. Operators can use gloves and wrappings, which alter the transmission of vibration from the tool to the hand. Gloves and wraps can improve comfort and reduce vibration at high frequencies. Gloves, and thus wrappings, can be considered a passive vibration control measure. An instrument operator may know the above aspects. The tool operator can use gloves and casings to improve comfort, reduce hand-arm transmission, or extend the allowable working life.

Over the past decade, the exploration of control systems has been driven by practical considerations, particularly those involving uncertain physical parameters of mechanical systems. One approach to account for such uncertainties is permitting each physical parameter to adopt a value within a defined range. Within this realm of complex uncertainty, the family of interval transfer functions serves as a valuable modeling structure (Dobra and Truşcã (2004)). The Popov diagram is crucial in absolute stability theory and adaptive control, especially when analyzing and synthesizing nonlinear feedback control systems. The experimental investigations propose Popov's diagram's geometry and rigid properties to assess the stability of human body parts, such as the upper limbs, shoulder, and back of brushcutter operators. The Popov algorithm evaluates the absolute strength of the hand-arm system, which is considered a closed-loop system. Gathering Popov graphs from the range transfer function family is essential in ensuring the robustness of the analysis.

2 Theoretical background

The hand–arm system represents a A closed–loop mechanical system characterized by subsystems with linear and non-linear behavior, which enjoy the relationship.

$$m = f\left(e\right) \ , \tag{1}$$

which establishes the link between the value of the input and that of the output at the instant t (Pennestri et al. (2005)). If the Eq.(1) meets the $f\left(0\right) = 0$, the system state space origin represents a point of equilibrium. If there the existence and uniqueness of the solutions, the first problem is to calculate, at the initial state and a given input, the evolution of the state $x\left(t\right)$ and the output $y\left(t\right)$ for $t \geq t_0$. Knowledge of the significant properties of state and output evolution represents interest in the proposed applications. This approach is qualitative and quantitative. According to the theory of stability, one of the most critical aspects in the qualitative analysis of the physical phenomenon is the study of the limiting properties and the asymptotic behavior of the solutions. The study of the stability of the hand-arm system consists of the evaluation of some aspects of the behavior of the hand-arm system in the presence of disturbances acting on the hand-arm system. The equations of the motion of the arm hand system are as follows:

$$\begin{aligned} \dot{x}\left(t\right) &= f\left[t, x\left(t\right), u\left(t\right)\right] \\ y\left(t\right) &= \mu\left[t, x\left(t\right), u\left(t\right)\right] \ , \end{aligned} \tag{2}$$

with $[t, x(t), y(t), u(t)] \in \mathcal{R}$ The solution of Eq.(2) is $x(t) = \phi(t, t_0, x_0, u)$ corresponding to the initial state $x(t) = x_0$ and an assigned input function $u(t)$. The hand-arm system can be stable or unstable:

- *Stability.* Suppose the evolution of the system's motion is relatively sensitive to disturbances in the initial state or on the input. In that case, the small perturbations generate minor variations in the system's evolution. The mechanical system is stable.
- *Unstable.* Suppose the evolution of the system's motion is sensitive to disturbances in the initial state or on the entry. In that case, a small perturbation alters the dynamic situation of the system corresponding to the absence of perturbations. The mechanical system is unstable.

2.1 Popov's theorem

The theorem of V.M. Popov obtains the proposed stability criterion. Given the system described by Eqs.(2). The state space origin is asymptotically stable if the following conditions occur:

- there is a real number $k > 0$ so that you can write

$$0 < \frac{f(e)}{e} < k \,, \tag{3}$$

- there is a real number α such that the function

$$(1 + \alpha s) G(s) + \frac{1}{k} \,, \tag{4}$$

a $F(s)$ function of complex variable is positive if

- has no poles with positive real part;
- its poles have no simple real part with real and positive residues;
- $Re[\jmath\omega] \geq 0$ per $0 \leq \omega \geq \infty$

The condition on the Eq.(4) becomes the following relation:

$$Re\left[(1 + \alpha\jmath\omega) G(\jmath\omega) + \frac{1}{k}\right] \geq 0 \,, \tag{5}$$

which can be used with the Nyquist plot of the function $G(\jmath\omega)$. It has the following relationship:

$$G(\jmath\omega) = \Re[G(\jmath\omega)] + \jmath\Im[G(\jmath\omega)] \,, \tag{6}$$

the function $\hat{G}(\jmath\omega)$ present the term $\Re[G(\jmath\omega)]$ as real part and the term $\jmath\omega\Im[G(\jmath\omega)]$ as imaginary part:

$$\hat{G}(\jmath\omega) = \Re[G(\jmath\omega)] + \jmath\omega\Im[G(\jmath\omega)] \,. \tag{7}$$

The Eq.(5) becomes a graphical condition on the function $\hat{G}(\jmath\omega)$. Indicate with x and y the real part and, respectively, the coefficient of the imaginary part of that function, the Eq.(5) has the following form:

$$x - \alpha y + \frac{1}{k} \geq 0 \,, \tag{8}$$

or

$$x \geq \alpha y - \frac{1}{k} \,. \tag{9}$$

The Eq.(9) is the condition that the points of the coordinates (x, y), representative vectors of the function $\hat{G}(\jmath\omega)$ are located to the right of a straight line intersecting the real axis at the point $(-1/k)$ and α. The Eq.(5) is satisfied if the graph of the function $G(\jmath\omega)$ is all included in the half–plane to the right of that line. With this interpretation of Eq. (5) Popov's theorem can offer the following reliefs:

- is determined whether the non-linearity meets the condition of Eq.(3) to determine the parameter k;
- you construct the graph of the function $\hat{G}(\jmath\omega)$ the function $G(\jmath\omega)$;
- you draw a line, passing through the $(-1/k, \jmath 0)$, that leaves the graph of $\hat{G}(\jmath\omega)$ to his right.

If the conditions of Popov's theorem are satisfied, the condition $x = 0$ is an asymptotically stable equilibrium state for the system under consideration. The condition is sufficient. If the conditions of the theorem are not satisfied, we cannot affirm anything. The procedure described verifies the stability of an assigned system.

Figure 1: Brush cutter position

3 Results

This section illustrates the experimental set-up and the results obtained from the experimental investigation.

3.1 Experimental set–up

The accelerations are recorded by a data logger AX6 activity. The measurement points are shaft of brush cutter and fingers, wrist, elbow, shoulder, back of worker. The brush cutter has the following characteristics 41.6 cc/2.0 kW–2.7 hp/ 8.5 kg (Fig.1).

3.2 Experimental investigations

Experimental investigations propose transfer functions with the input at the crankshaft side of the brush cutter and the output at the fingers, wrist, elbow, shoulder and back of the operator. Transfer functions consider the relationship between the input, represented by the rotation tree, and the outputs, such as the fingers of the right hand (Fig.2), the wrist (Fig. 3), the elbow (Fig.4), the shoulder (Fig.5) and the back of the operator (Fig.6). The stability analysis of transfer functions implements Popov's theorem. The stability analysis examines the development of the relationship $\omega\Im(\jmath\omega)$ vs. $\Re(\jmath\omega)$ by the Popov criterion. The Popov line may have an arbitrary orientation, or the angle relative to the real axis (Popov (1960), Yoshida et al. (2013)).

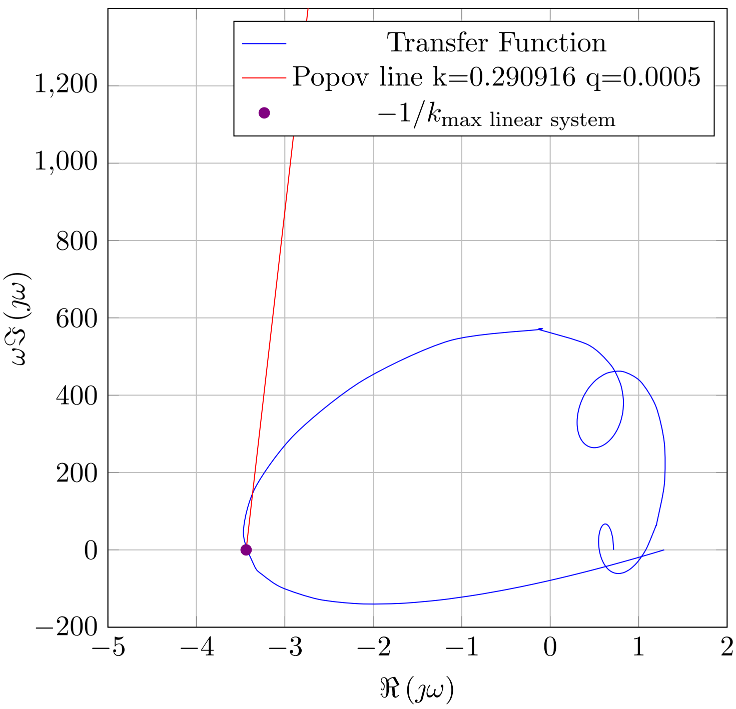

Figure 2: Transfer Function stability of shaft–fingers relationship

4 Discussion

Kickback and work overload are the leading causes of accidents caused by using a brushcutter for weed control work. The lower and upper limbs represent the damaged parts of the body (Kashima and Uemura (2010)). According to research, the Raynaud phenomenon occurs in 0.4% of individuals who have used shrubs for four years, 4.0% after ten years, and 9.2% after 18 years. The prevalence of this condition is twice as high in chainsaw users compared to those who use bush cutters. Typically, bush cutter users experience the Raynaud phenomenon after approximately $1,000$ hours of work, which causes mild disturbances in their upper limbs due to the vibration of the equipment (Futatsuka (1979)). The isolator is between the tool and the human hand. Mechanical impedance evaluates the behavior of the human hand (Seto (1983)). The brushcutter develops Raynaud's disease in workers due to significant vibrations. The type of handle can reduce the magnitude of vibration (Daikoku (1991)). Rubber bushings can effectively reduce the vibration of the handle (Okubo et al. (2014)).

Popov's algorithm allows you to evaluate robustness problems with parametric uncertainty and non-linear feedback gains (Moore and Anderson (1968), Yakubovich (2002)).

The theory of stability for nonlinear time systems is an invaluable resource. Mathematical models, in the form of nonlinear differential and integral equations, are utilized to describe such systems and are linearized or perturbed around a periodic solution (Cavacece et al. (2021)) . These equations also vary in time to model the anxious behavior of dynamic systems more accurately. During working conditions, the hand-arm system exhibits nonlinear behavior.

Some algorithms develop the study of local stability properties of linear systems by analyzing the stability of a linearized representation. The criterion of Popov's theorem evaluates the strength of a nonlinear system by a graphical method. Popov's theorem considers the function of the frequency response of the nonlinear system and a line with an assigned slope q. If the frequency response function graph is included in the region bounded by the line with an assigned slope q, the nonlinear system is stable. The interest of research lies in a nonlinear system's

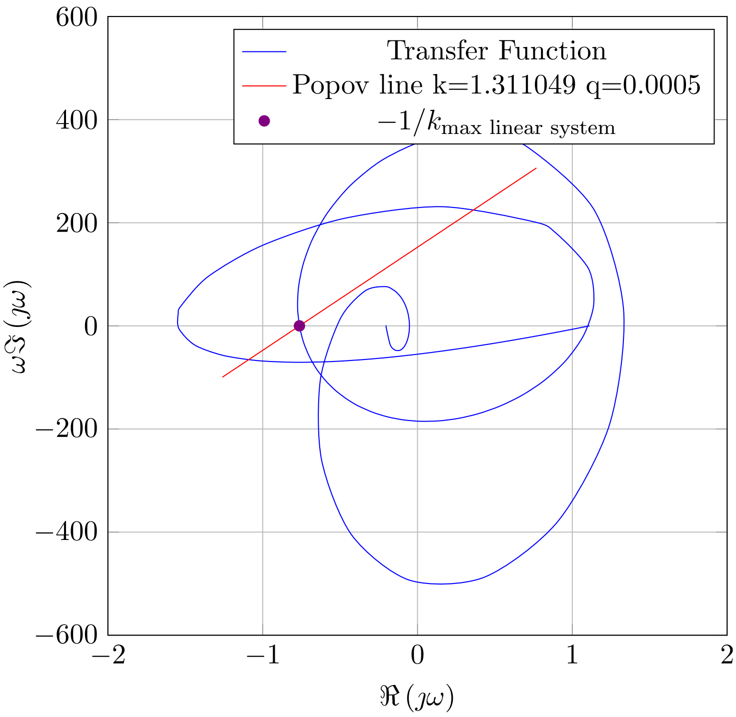

Figure 3: Transfer function stability of shaft–wrist relationship

stability or non-stability characteristic. The hand-arm system comprises a set of individual linear or nonlinear interconnected systems, such as elbow and shoulder wrist fingers. The research aims to assess the overall stability of the entire hand-arm system by analyzing individual systems such as the elbow shoulder, wrist, fingers, and back. Previous research assesses the exposure of the hand–arm system to vibration by analyzing an overall parameter A(8).

This is a measure of the duration of vibration exposure, as in, how long you are exposed. So, the A(8) part of the exposure limits defined in the regulations is telling us that the limits are for an average over 8 hours. The m/s^2 part tells us the level of vibration applied on human hand arm system. The analysis developed using the global parameter A(8) shows the following:

- *Hand arm vibration.* The exposure limit value (ELV) is the maximum vibration value for an operator and a single day. The ELV parameter represents a daily exposure of 5 m/s^2 A(8) for vibration on the hand–arm system. The action exposure value of 2,5 m/s^2 A(8) means a high risk for workers. Workers should use vibration-damping gloves to protect themselves from HAV–prolonged exposure to white finger syndrome (WFS) or Raynaud syndrome.
- *The vibration of the whole body.* Mechanical vibrations, acting on the feet or other parts of the body, produce mechanical vibrations to the whole body. Prolonged exposure to WBV can be associated with severe lumbar pain. For whole-body vibration, the ELV parameter allows a daily exposure of 1.15 m/s^2 A(8), and the Exposure Action Value (EAV) allows 0.5 m/s^2 A(8).
- *Biomechanics of the spine.* Brush cutter is supported by a human operator on his shoulders and, simultaneously, on his back. The arms and hands control the brush cutter. The posture of human operators for the operation of mowing the grass is standing and slightly bent forward. The human spine is exposed to mechanical vibration in the following directions: according to shoulder direction and foot direction. The weight of the brush cutter

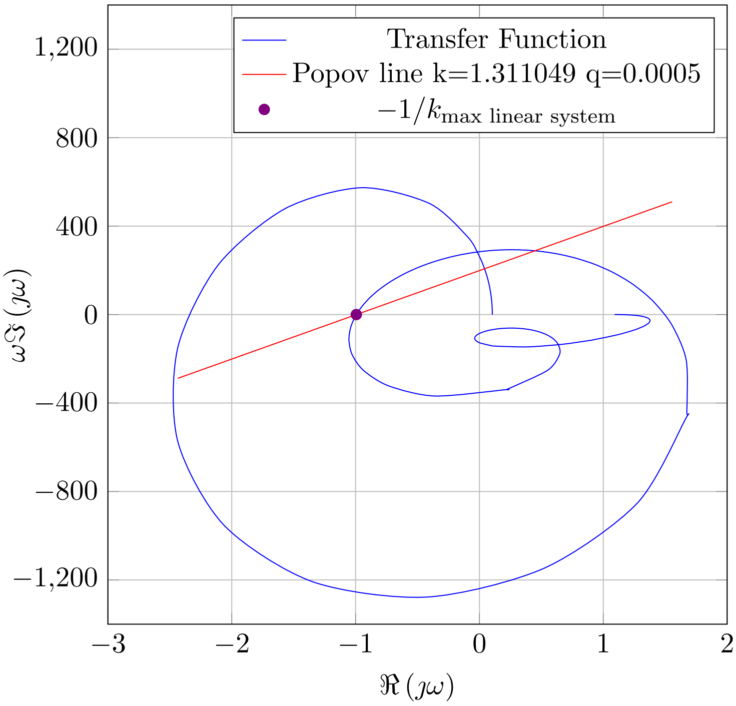

Figure 4: Transfer function stability of shaft–elbow relationship

is about 9 Kg providing mechanical stress on the human spine. Measurements were made only on the human body and under full load. The accelerometer was on the right hand.

- *Vibration reduction.* The drive shaft, cutting attachment, and motor represent the parts that emit vibrations. Optimization of shaft construction reduces low-frequency vibration. Increasing the wall thickness of the shaft tube (but not its weight) in the area for mounting the crankshaft bearing and handles can reduce mechanical vibration by 20% − 30%. The steering wheel handles from the materials have anti-vibration characteristics using elastomers.
- *Ergonomics of the handle.* The diameter of the handle assures the operator to hold the tool with the hand opposite to the thumb, in order to use the muscle of the forearm. The shape of the handle has the shape of the hand to accommodate the anatomy of the operator's hand (Cavacece et al. (2023)).

The stability analysis by Popov's theorem allows us to evaluate the stability of the individual interconnected parts. The advantage is identifying the critical points of the subsystems constituting the system subjected to mechanical vibration. In particular, the proposed application highlights vital issues at the wrist and elbow of the operator. On the other hand, the fingers, shoulder, and back, subjected to mechanical vibrations, have a stable behavior. The stability assessment proposes a geometric construction to determine the region bounded by a straight line with an assigned slope and passage through a point.

5 Conclusion

The objective of this research is to investigate the transmissibility of vibrations from an instrument that is held and guided by a worker. The drive shaft, cutting attachment, and motor are the components that emit vibrations. The thickness of the shaft tube in the area for mounting the crankshaft bearing and the ergonomics handles can reduce mechanical vibration by

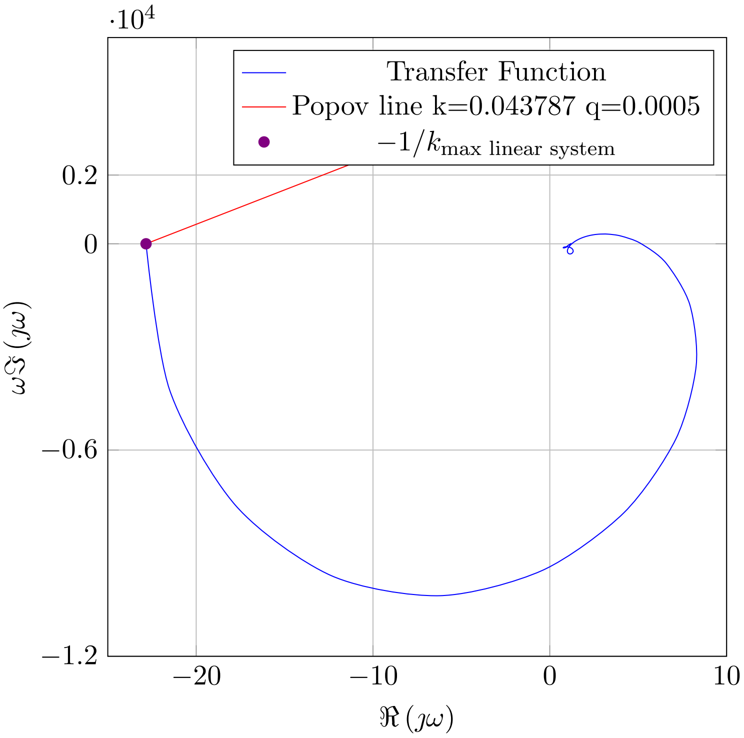

Figure 5: Transfer function stability of shaft–shoulder relationship

$20\% - 30\%$. Materials steering wheel handles can offer anti-vibration features using elastomers. The attenuation of vibration is noticeable from the fingers to the elbow, elbow and back of the worker. The poles are positioned at low frequencies. The maximum energy content is manifested at low frequencies.

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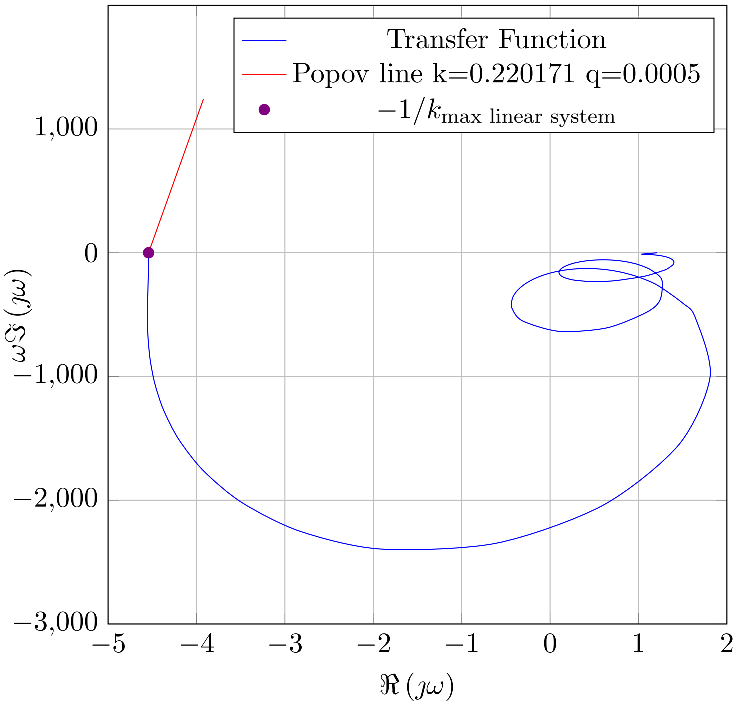

Figure 6: Transfer function stability of shaft–back relationship

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