Optimum design of integrated feed drive and ball screw nut

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Abstrakt

Na obráběcí stroje jsou v oblasti oblasti pohonů pohybových oskladeny stale vyšší požadavky na dosažení vysoké polohové přesnosti při vysokých hodnotách rychlostí a zrychlení. Předpokladem konstrukce takových pohonů je mechanická stavba pohonu s vysokými frekvenčními vlastnostmi. Jednou z možností dosažení vyšších dynamických vlastností servopohonu je použití integrovaného servomotoru a kuličkové matice. Příspěvek se zabývá rozměrovou a konstrukční optimalizací návrhu elektromatice, realizací vybraného řešení a porovnáním modelu s klasickým uspořádáním pohonu.

Klíčová slova

Obráběcí stroj, servopohon, pohybová osa, elektromatice.

Abstract

Machine tools feed drives with ball screw are under higher demands to achieve high positioning leading at high dynamics movements. To meet these requirements it is needed to build machine tools feed drives with high frequency characteristics. Using integrated feed drive and ball screw nut is one of ways how to reach feed drive with higher dynamical properties. The paper describes dimensional and design optimization of integrated feed drive and ball screw nut, describes selected design and shows comparison with belt gear feed drive.

Keywords

Machine tool, feed drive, ball screw feed drive, ball screw nut

1. Introduction

Design of ball screw design can be arranged various configurations. Most often is the arrangement with rotating ball screw, whereby the driving torque from motor can be transmitted e.g. by a coupling or a belt gear. Another type of configuration is based on non-rotating ball screw. In this case, ball screw can be connected to the moving part of the motion axes, on the ball screw is a part of machine tool base and motor is joined with the moving part of the moving axes.

The goal of this paper is to show the benefit of feed drive in configuration of integrated feed drive with ball screw nut to dynamical properties compared with more often belt gear configuration.

2. Basic properties of ball screw feed drive

The common machine tool feed drive design in configuration one side fixed ball screw ball screw nut belt gear support is shown in *Fig. 1*.

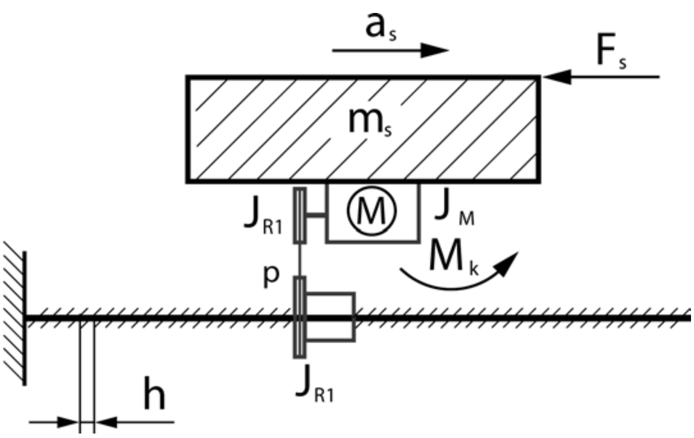


Fig. 1. *Machine tool feed drive design with fixed ball screw and belt gear*

The achievable acceleration on support a_s is the ratio between the force F_s acting on support and m_{red} is the feed drive total mass reduced to the translatory coordinate of the support.

$$a_S = \frac{F_s}{m_{red}} \tag{1}$$

m_{red} is linear depended on total masses and moment of inertia of the feed drive moving parts and nonlinear depended on pitch.
This design shown on *Fig. 1* gives the reduced masses as shown in equation *(2).*

$$m_{red} = m_s + \frac{(J_M + J_{R1}) \cdot p^2}{h^2} + \frac{J_{R2}}{h^2} \tag{2}$$

The reduced masses are the sum of support mass m_s and the moment of inertia of rotating parts – motor J_M, pulley on motor J_{R1} multiplied by gear ratio powered by two and divided by the ball screw pitch h powered by two and inertia of pulley J_{R2} divided by the ball screw pitch h powered of two. J_{R2} represents all rotating parts belonging to pulley 2 (nut and bearing's inner rings)
Another design of the machine tool feed drive is shown in *Fig. 2*.

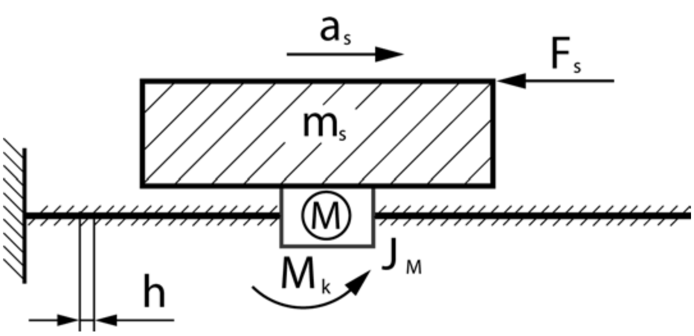


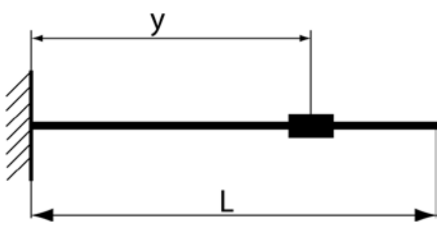
Fig. 2. *Machine tool feed drive design with fixed ball screw and rotating ball screw nut*

This design gives the reduced masses as shown in equation *(3).*

$$m_{red} = m_s + \frac{J_M}{h^2} \tag{3}$$

The reduced masses are also sum of support mass and the moment of inertia of rotating parts divided by the ball screw pitch powered by two. In this case J_M represents moment of inertia of all rotating parts such as the motor rotor, ball screw nut and bearing's inner rings and balls.
Smaller reduced masses of the motor nut design it is possible to achieve either higher acceleration in the case of using the same motor or to use a smaller motor enables to achieve the same acceleration.
The feed drive design is characterized by a static compliance, depending on compliance of used components and also given by position of ball nut on the screw.
Equations for axial and torsion compliance of ball screw recomputed into its axial direction are shown in *Table 1*.

Table 1. *– Static compliance for selected ball screw design [4]*

ball screw design case	scheme	thrust – pressure compliance	reduced torsion compliance
III. stationary one-side axial fixed ball screw with rotating ball screw nut		$c_{T1} = \dfrac{4 \cdot y}{\pi \cdot D^2 \cdot E}$	$c_{K1} = \dfrac{32 \cdot h^2 \cdot y}{\pi \cdot D^4 \cdot G}$

3. Real machine tool feed drive design

For experimental horizontal milling machine of one of Czech machine tool producers has been developed new design of feed drive with integrated ball screw nut, see *Fig. 3*.

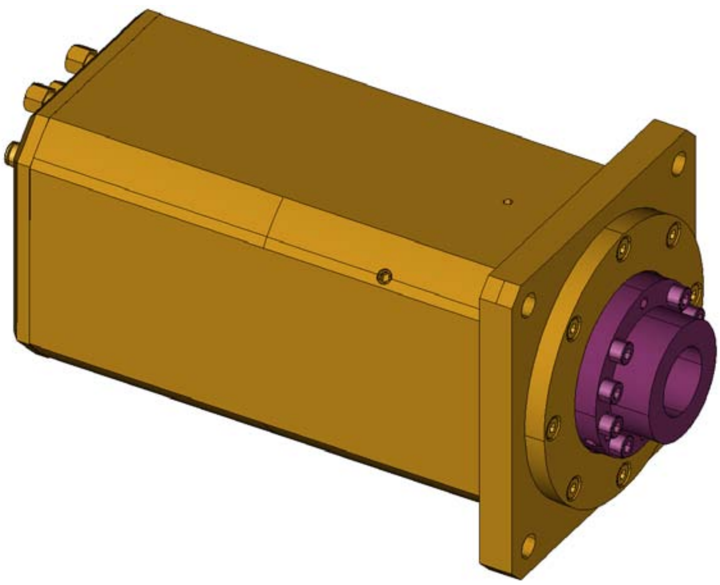


Fig. 3. *Integrated feed drive and ball screw nut*

Cut of the final design is shown on *Fig. 4*. The flanged ball screw nut is joined to ball screw nut tube with pressed engine rotor. Whole tube is connected with stator part by front axial-radial bearings and by rear radial bearings. Incremental rotary encoder in positioned in the rear section of whole assembly. Stator parts are represented by golden color, rotating parts by red color. Used components are specified in *Table 2*.

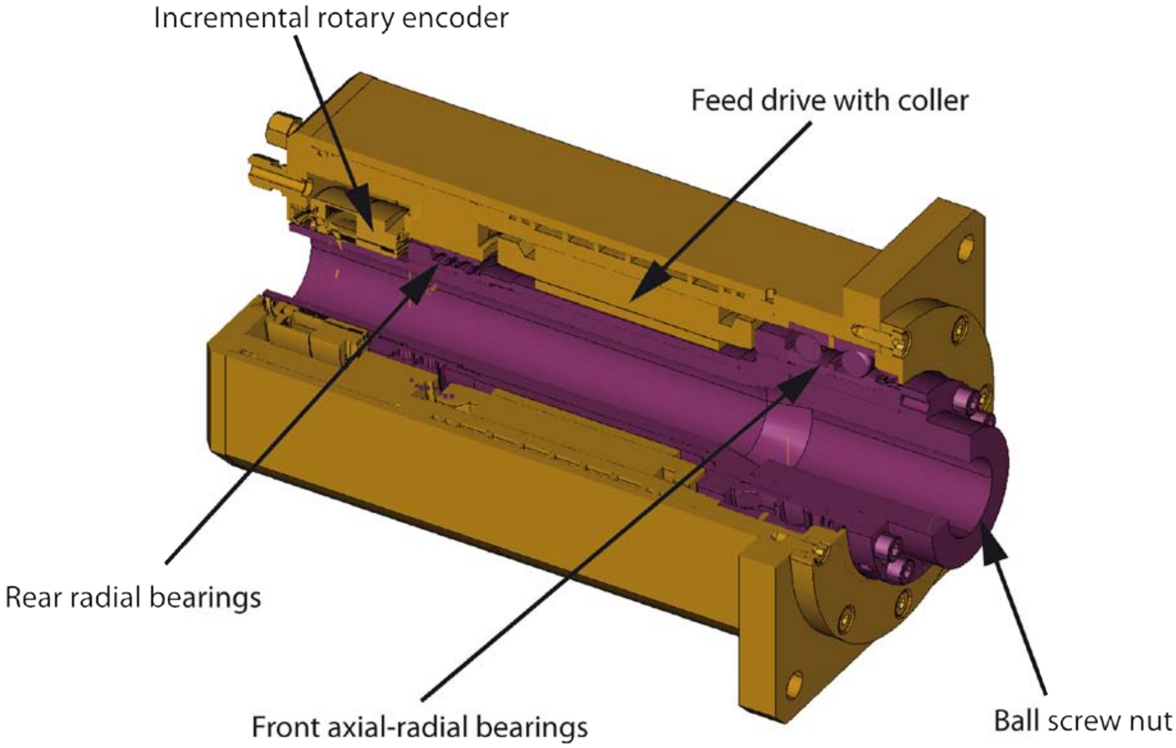


Fig. 4. *Integrated feed drive and ball screw nut - cut*

Table 2. *– Integrated feed drive and ball screw nut used components*

name	vendor	type	description
Ball screw nut	KŠK Kuřim	APQR 40x40	Preloaded flanged ball screw nut
Feed drive	VUES Brno	AFW635N	
Front axial-radial bearings	NSK	7017 A5TR	Two bearings in configuration “O”
Rear radial bearings	NSK	7911 A5TR	

4. Coupled models of feed drive and machine structure

To perform a comparison of the considered feed drive design with integrated ball screw nut and belt gear design it is useful to use feed drive complex model approach. Within the complex model, model of the feed drive mechanical structure coupled with the machine tool frame is implemented in the feed drive control model.

4.1. Model of flexible machine structure

Mathematical description of machine frame can be implemented into the model of servoregualtion in Matlab/Simulink in the form of State-Space model. However, common FEM programs do not work with State-Space models and do not offer a direct possibility of assembling the State-Space matrices.There are generally two ways how to carry out the transformation – the first one is based on the knowledge of mass, damping and stiffness matrixes of the FEM system, the other one goes out from equations of motion written in modal coordinates and solution of modal analysis. It is obvious, that the latter way is more

advantageous, since it provides the possibility of exporting just few interface nodes of FEM model and selection of only such eigenmodes of the system, which are relevant with respect to a certain transfer function investigated. Thanks to it very small size State-Space matrixes can be obtained, whereby the quality of original FEM model is still kept without the need of its reduction in physical coordinates.
System of State-Space equations is written as

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A} \cdot \mathbf{x} + \mathbf{B} \cdot \mathbf{u} \\ \mathbf{y} &= \mathbf{C} \cdot \mathbf{x} + \mathbf{D} \cdot \mathbf{u} \end{aligned} \tag{4}$$

where *x* is the state vector of the system, *u* vector of forces and *y* output vector. Matrices *A* and *B* are input matrices, matrices *C* and *D* are matrices of the system output. From modal analysis the matrix of normalized eigenvectors *V* and spectral matrix of eigenfrequencies *Λ* can be obtained:

$$\mathbf{V} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \dots & \mathbf{v}_m \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1m} \\ v_{21} & v_{22} & \cdots & v_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{n1} & v_{n2} & \cdots & v_{nm} \end{bmatrix} \qquad \mathbf{\Lambda} = \begin{bmatrix} \omega_1^2 & 0 & \cdots & 0 \\ 0 & \omega_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \omega_m^2 \end{bmatrix} \tag{5}$$

Basic equation of motion can then be written in modal coordinates as

$$\mathbf{E} \cdot \ddot{\mathbf{q}} + \mathbf{C}_q \cdot \dot{\mathbf{q}} + \Lambda \cdot \mathbf{q} = \mathbf{V}^T \cdot \mathbf{f} \tag{6}$$

where *E* is unity matrix, C_q matrix of modal damping, *q* vector of modal coordinates and *f* vector of forces. It can be shown, that after the substitution the State-Space matrices get the form

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{E} \\ -\Lambda & -\mathbf{C}_q \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{V}^T \end{bmatrix}$$
$$\mathbf{C} = \begin{bmatrix} \mathbf{V} & \mathbf{0} \end{bmatrix}, \qquad \mathbf{D} = \begin{bmatrix} \mathbf{0} \end{bmatrix}. \tag{7}$$

4.2. Feed drive mechanical part description and connection with the machine tool frame

Mechanical structure of the ball screw feed drive is described separately from the machine frame FEM model. A discrete model with parameters representing the inertial and stiffness characteristics of the feed drive mechanical components is created, whereby the ball screw is modeled as a 1D continuum with both the axial and radial DOF's, between which a constraint equation is set. System of equations of motion of this system is transformed into the State-Space. General scheme of ball screw feed drive model with motor, coupling and axially one side fixed ball screw connected with the machine tool frame shows *Fig. 5*.

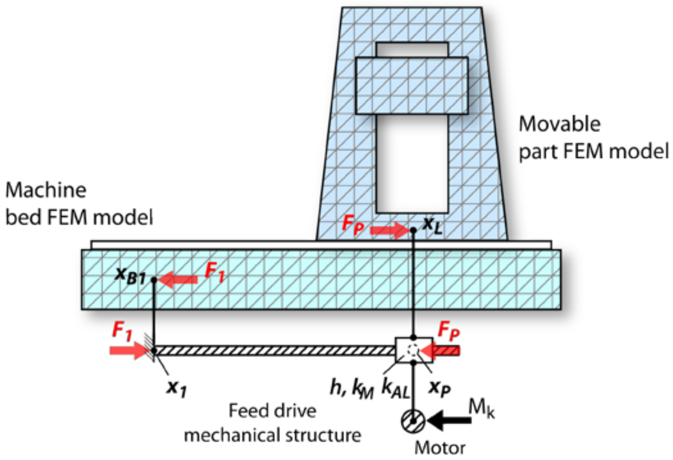


Fig. 5. *Discrete model of the ball screw feed drive and its connection to the machine frame*

Symbolic scheme of the servoregulation model with two State-Space blocks representing the ball screw feed drive and machine frame, between which a force interaction is set shows *Fig. 6*.

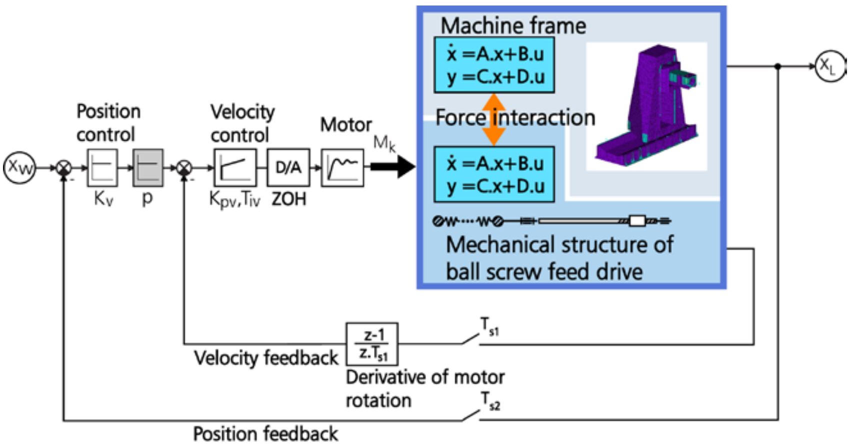


Fig. 6*. Model of servoregulation with State-Space blocks of the machine frame and ball screw feed drive.*

5. Complex model of the real machine tool

5.1. Description of the machine tool FEM model anz Z-axis drive design

Complex mechatronic model was created for a real experimental milling centre of one of the Czech machine tool producers. Machine tool *Z*-axis features the design of static column which carries *Y*-axis with spindle unit and movable rotary table for the workpiece. Volume mesh of the machine shows *Fig. 7*. FEM model for the modal analysis, which is solved in the I-Deas software, keeps a free movement of *Z*-axis in *Z* direction. Mechanical part of the *Z*-axis feed drive is composed of the fixed ball screw and motor with integrated ball screw nut. Model of the Z-axis feed drive and its connection with the machine frame was created according to the schemes on *Fig. 7* and *Fig. 8*.

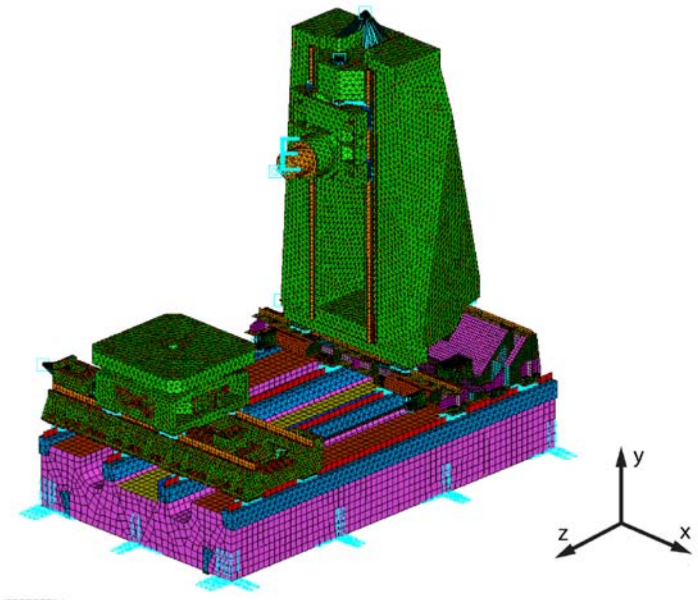


Fig. 7. *FEM model of machine tool.*

5.2 Simulation of the velocity loop dynamic properties

An insight into the feed drive dynamical properties can be obtained through the velocity control loop transfer function relates to the feed drive dynamic properties. First amplitude drop which relates to the oscillation of the mechanical system with motor locked occurs at a antiresonance frequency ω^*_M.Theory of regulation shows [e.g. 3], that there is a direct connection between the value of ω^*_M and the position loop gain factor *Kv*. Therefore, good determination of ω^*_M frequency provided by simulation model is profound for relevant estimation of *Kv* factor. Simulations have been performed with the velocity loop model created in the continuous Laplace space. Current loop is replaced with a transfer function characterized by a 1000 Hz bandwidth and a transport delay.

Feed drive with belt gear was compared to feed drive with motor. Simulations were performed for two type of workpieces – 0 kg and 2 500 kg. Results of the ϕ_M/M_k frequency response simulations and comparison of both variants of the feed drive design are shown in *Fig. 8* and *Fig. 9*.

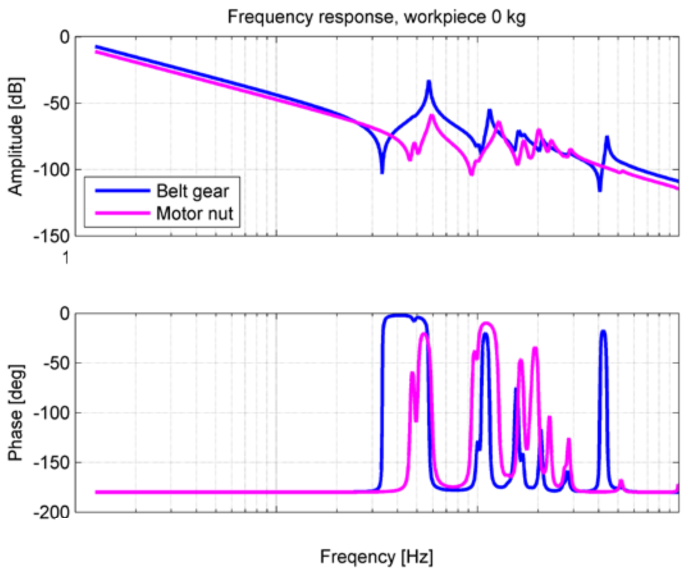


Fig. 8. *Frequency transfer of velocity loop for workpiece 0kg..*

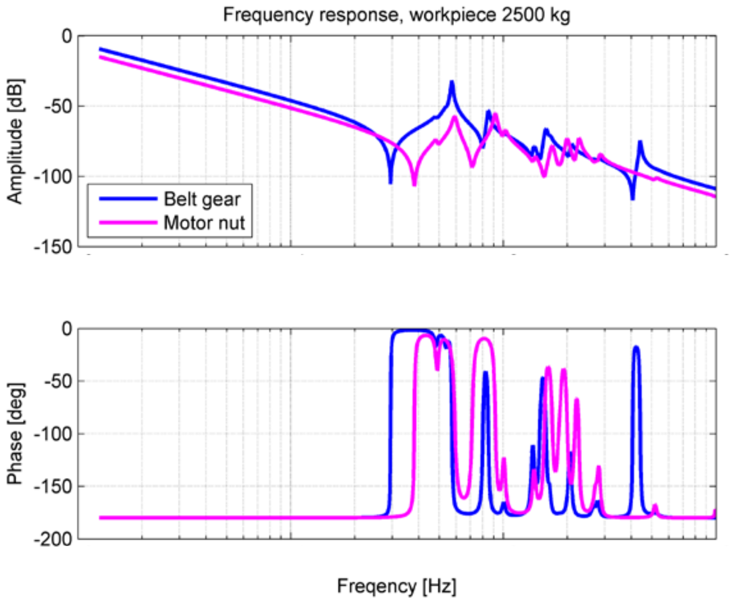


Fig. 9. *Frequency transfer of velocity loop for workpiece 2 500kg..*

It may be seen that using feed the drive without belt gear and with integrated ball screw nut increases significantly the first antiresonance frequency. For the empty table the first antiresonance frequency is increased by 18%;m if the workpiece of 2 500kg is considered, the increase is 10%.

6. Conclusion

The paper shows the benefit of using the integrated motor nut on the ball screw feed drive design. Compared to the common case of the feed drive with belt gear it has been demonstrated, that the dynamic properties of the feed drive can be significantly improved. The first antiresonance frequency, the value which directly relates to the achievable value of the position control loop gain factor *Kv*, is improved by 36 %, if the empty table of the motion axis is considered. At the same time the feed drive mass reflected to the translator coordinate is reduced by 18 %

7. Acknowledgement

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8. List of used symbols

a_s	acceleration	$[m \cdot s^{-2}]$
C_T	compliance	$[m \cdot N^{-1}]$
C_k	compliance	$[m \cdot N^{-1}]$
E	Young's modulus of elasticity	[Pa]
F_s	force	[N]
G	shear modulus	[Pa]
h	pitch	[m]
J_M	moment of inertia	$[kg \cdot m^2]$
J_C	moment of inertia	$[kg \cdot m^2]$

J_S	moment of inertia	[kg·m^2]
J_{R1}	moment of inertia	[kg·m^2]
J_{R2}	moment of inertia	[kg·m^2]
L	length	[m]
m_{red}	mass	[kg]
m_s	mass	[kg]
x	state vector	[-]
y	distance	[m]
u	vector of forces	[-]
y	output vector	[-]
A	input matrix	[-]
B	input matrix	[-]
C	output matrix	[-]
D	output matrix	[-]
V	spectral matrix	[-]
Λ	matrix of eigenfrequencies	[-]
E	unity matrix	[-]
C_q	matrix of modal damping	[-]
q	vector of modal coordinates	[-]
f	vector of forces	[-]
ϕ_M	angle	[rad]
M_k	torque	[N·m]
K_v	gain factor	[-]
ω^*_M	frequency	[Hz]

9. References

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