Deformation of Screw Machine Housing under Force Field and its Consequences

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Kurzfassung

Die, durch die Einwirkung des Kraftfeldes im Arbeitsraum verursachte, Deformation eines vereinfachten Modells eines Schraubenmaschinengehäuses wird berechnet. Im theoretischen Fall sind die Achsen der starren Rotoren parallel. Unter dem Einfluss der Deformation des Gehäuses und der Lager, die durch die Krafteinwirkung hervorgerufen wird, ändert sich die parallele Anordnung der Rotoren in eine räumliche Aufstellung. Bei einer Schraubenmaschine mit Flüssigkeitseinspritzung ändert sich die relative Wälzbewegung der Rotoren in eine Schraubenbewegung um eine Achse, die durch die gegenseitige Lage der Rotoren festgelegt wird. Die relative Rotorbewegung wird mittels der kinematischen Eigenschaften des Plücker-Konoids analysiert. Die Kraftfelder der Rotoren werden durch Schrauben ersetzt, deren gegenseitige Kraftwirkung berechnet wird. Die Analyse der Deformation der Lagerung der Rotoren wird mit Hilfe einer Empfindlichkeitsuntersuchung durchgeführt. Die Kurvenberührung, im Fall der Parallelachsen, ändert sich in eine Punktberührung und in diesem Fall kommt es zu einer wesentlichen Erhöhung der Berührungsbeanspruchung.

Abstracts

The deformation of the simplified model of screw machine housing caused by the force field in the work space is determined. Theoretically, axes of both rotors are parallel. After the housing and bearing deformation which is evoked by the action of force, the parallel position of rotors changes into spatial arrangement and, in case of the injected screw machine, relative rotary motion changes into relative screw motion, twist, around some axis, which is determined by mutual position of the axes of both rotors. The relative motion between the two rotors is analyzed with means of Pluecker's conoid. The force fields of both rotors are replaced with wrenches and their mutual acting is determined. The bearing deformation in the different direction is investigated with the use of sensitivity analysis. The curve of correct contact in case of parallel axes of rotors changes into contact at point and so the contact strain in case of spatial arrangement of axes increases significantly.

1. Introduction

This contribution is devoted to screw machines with liquid injection in which tooth surfaces of rotors, beside of creation of workspace and its seal, ensure of kinematic and force accouplement between rotors. Axes of both rotors are parallel and relative movement is determined with the rolling of rolling cylinders of both rotors. In this case it is possible kinematic problems and some solution of static and dynamic problems to think as planar problem in cross sections of rotors. Under the influence of the force field, temperature field and dynamic activities the parallel arrangement of rotors axes changes into spatial position

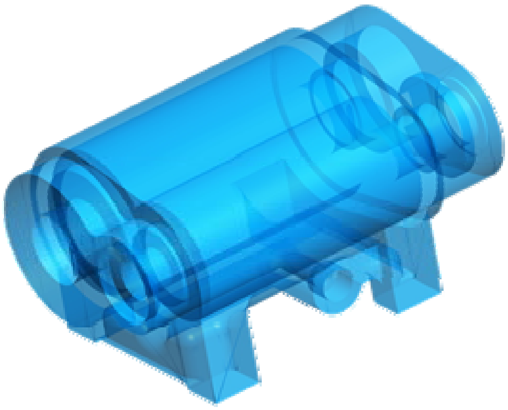

Fig 1: Simplified screw machine housing

and the relative rotary motion changes into relative screw motion, twist, around some axis which is determined by mutual position of rotor axes. This axis is a straight-line of the surface of Pluecker's conoid [1] which is a skew straight-line surface. Kinematic properties of Pluecker's conoid were applied to the determination of the axis of relative screw motion, twist, of the rotors by spatial arrangement of their axes. In this paper only force field is considered. The deformation of simplified model of screw machine housing, Fig. 1, which is loaded with non-stationary force field that is caused by compression of medium is determined. The force field affects the housing partly directly and partly by means of both rotors. Force fields, that effect on each of the rotors, are replaced by force screws, wrenches. The force field is considered in the phase just before the opening of discharge. The mutual actuating of both wrenches is determined and the influence of the quantities of bearing displacement in different directions upon this actuating is investigated with using of sensitivity analysis. The general position of axes of the rotors caused the change in a contact of teeth of the rotors [6] and consequently, by injected screw compressors, alternation of speed ratio and the rise of undesirable clearances between teeth. The one's own deformations of screw rotors, i.e. force and temperature deformation [3], [5] are not involved into solution and likewise the temperature deformation of the machine housing is not accepted.

2. Force field

The force field, which is considered in the phase just before the opening of discharge, is given by the pressures in chambers of the screw machine, Fig. 2, Fig. 3. Gas compression in work space is described by adiabatic change $pV^{\kappa} = const$, $\kappa = 1,4$. Numerical solution was made for next basic geometric parameters of the screw machine: axes distance a_w = 85mm, gear ratio i_{32} = 1,2, where 3 is male rotor and 2 is female rotor, helix angle on the rolling cylinder of both rotors γ = 45°, length of tooth part of both rotors l = 193,8 mm. Pressures in chambers of separated work spaces in dependence on angular displacement φ_3 of male rotor are given in Tab. 1, where position for φ_3 = 0° corresponds with the situation just before the opening of the discharge. From the pressure of separated work spaces, in position of rotors that is given by angle φ_3, the instantaneous force field for each rotor was defined. The force field which consist from forces

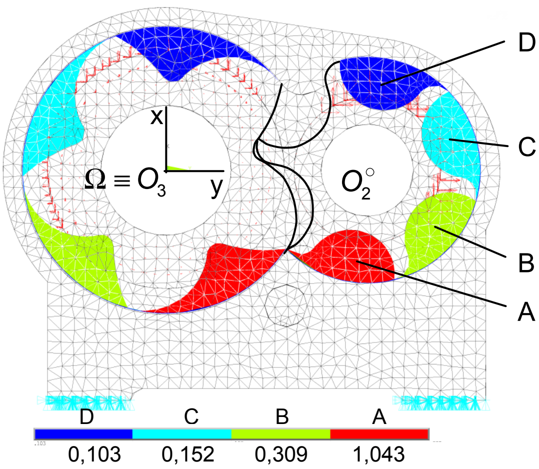

Fig 2: Cross section of screw compressor housing

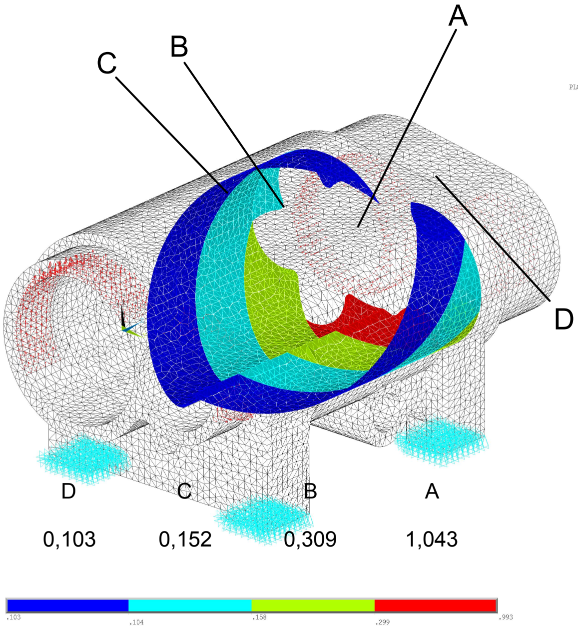

Fig 3: Simplified model of screw machine housing with marked work spaces

and couples in nodes of rotor axes, was determined in accordance with relations $\mathbf{F}_k = \sum_{i=1}^{s} \mathbf{F}_i$, $\mathbf{M}_k = \sum_{i=1}^{s} \mathbf{M}_i$, where $\mathbf{F}_i$, $\mathbf{M}_i$ are results of the pressure on elementary area of tooth surfaces transformed into nodes of rotor axes. Index k determines the node and index s the area which appertains to an appropriate node. Resultant of the force field is given with expression $\mathbf{F} = \sum_{k=1}^{n} \mathbf{F}_k$, $\mathbf{M} = \sum_{k=1}^{n} \mathbf{M}_k + \sum_{k=1}^{n} \mathbf{r}_k \times \mathbf{F}_k$, where n is a general number of nodes which is the same for each rotor. The position of the node on each of the axes of rotors is determined with position vector $\mathbf{r}_k = \left[0\ ,\ 0\ ,\ (k-1)\dfrac{l}{n-1}\right]^{\mathrm{T}}$, where l is the length of tooth parts of rotors. Further it is possible the both resultants **F**, **M** replace with force screws, wrenches, which are determined with direction of forces and position vectors $\mathbf{r}_{E_i} = \dfrac{\mathbf{F}_i \times \mathbf{M}_i}{|\mathbf{F}_i|}$, i = 2, 3. Components of wrenches for the position $\varphi_3 = 0°$ are presented in Tab. 2 and wrenches of separated rotors are demonstrated in Fig. 4. Wrenches effected on rotors are in equilibrium with reaction forces at rotor sealing according to equations

$$\begin{aligned} &\mathbf{F}_i + \mathbf{R}_{A_i} + \mathbf{R}_{B_i} = \mathbf{0}, \\ &\left(\mathbf{r}_{B_i} - \mathbf{r}_{A_i}\right) \times \mathbf{R}_{B_i} + \mathbf{r}_{A_i} \times \mathbf{F}_i + \mathbf{M}_i + \mathbf{M}_{Si} = \mathbf{0},\ i = 2, 3, \end{aligned} \tag{1}$$

where $\mathbf{M}_{si}$ are thought moment of the couple added to equation for equilibrium. Components of forces acting at place of bearings on machine housing, $\mathbf{A}_{ji} = -\mathbf{R}_{ji}$, j = A, B, i = 2, 3 in rotor position that is given by the angular displacement $\varphi_3 = 0°$ are shown in Tab. 3.

Table 1: Pressures in work spaces

φ_3 [°]		0°	18°	36°	54°
A	p [Mpa]	1,043	0,693	0,506	0,364
B		0,309	0,244	0,206	0,179
C		0,152	0,138	0,120	0,109
D		0,103	0,103	0,103	0,103

Table 2: Components of wrenches and their location for $\varphi_3 = 0°$

	Male rotor			Female rotor		
Coordinate	$\mathbf{F}_3$ [N]	$\mathbf{M}_{o3}$ [Nm]	$\mathbf{r}_{E_3}$ [m]	$\mathbf{F}_2$ [N]	$\mathbf{M}_{o2}$ [Nm]	$\mathbf{r}_{E_2}$ [m]
x	2048,51	-22,85	0,023	2287,26	-6,27	0,009

y	-2386,28	26,62	-0,044	2407,82	-6,60	0,012
z	-1251,39	13,96	0,122	-313,54	0,86	0,153

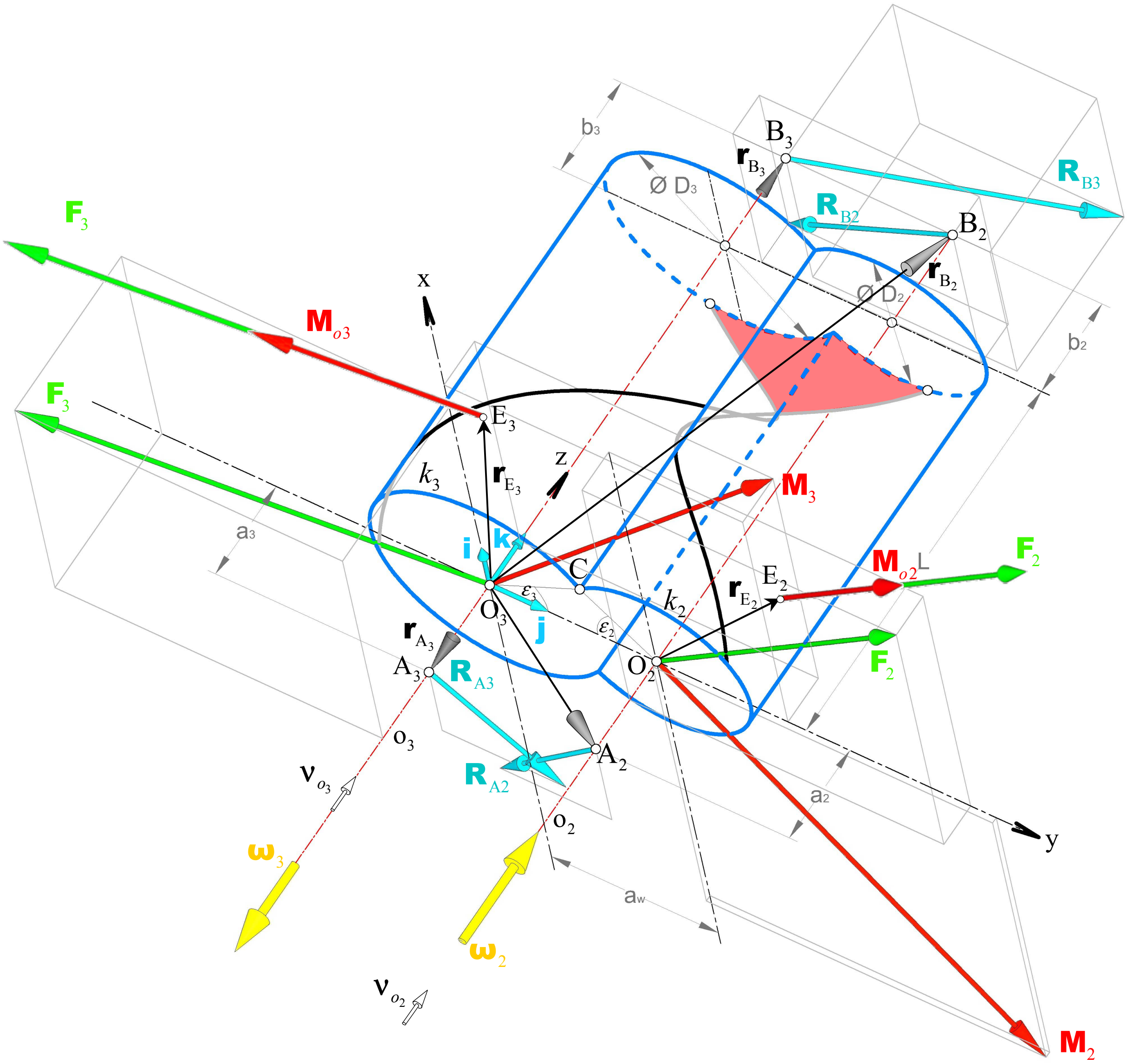

Fig 4: Wrenches and reaction forces at seating of rotors

Table 3: Components of forces at seating of rotors

Components	$\mathbf{A}_{A3}$	$\mathbf{A}_{B3}$	$\mathbf{A}_{A2}$	$\mathbf{A}_{B2}$
x	670,96	1 377,55	821,17	1 466,09
y	-901,69	-1 484,59	812,40	1 595,42
z	0,00	-1 251,39	0,00	-313,54

3. Deformation of screw machine housing

The numerical solution of screw machine housing deformation was made with software ANSYS®. Geometrical model, Fig. 3, was created with quadrilateral elements with ten nodes. Solution was made on the assumption that deformation is described by Hooke's law and bearings are ridged. Maximum of local housing displacement is 5,346 μm. Subsequently, the elastic deformation of tapered roller bearing radial thrust bearing and roller bearings was solved. Displacements of bearing centres are presented in Tab. 4. On the basis of these values the instantaneous axes position of rigid rotors was established, i.e. the position vectors $\mathbf{r}_{O_i^\Delta}$ of points O_i^Δ, i = 2, 3, in the deformed position was determined. Situation is presented in Fig. 5 where O_i^Δ, i = 2, 3 are newly deformed positions of original points O_i.

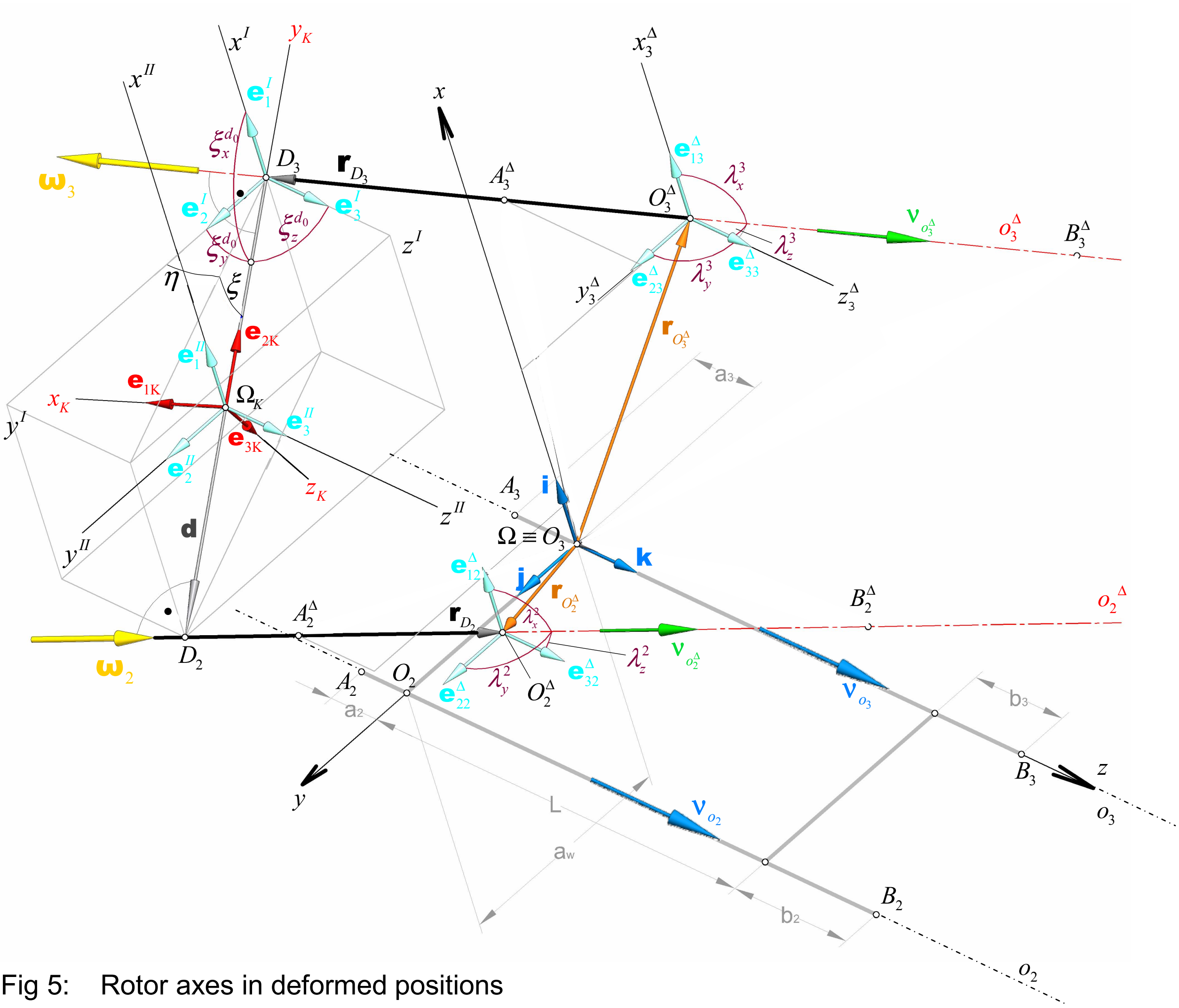

Fig 5: Rotor axes in deformed positions

4. Pluecker's conoid

From the kinematic point of view, Pluecker's conoid, which is skew straight-line surface of 3rd degree, has properties that we can exploit to determine of axis o_{32}^Δ of relative screw motion both rotors in case of spatial arrangement their axes. Each of three axes i.e. o_3^Δ, o_2^Δ and o_{32}^Δ lies, Fig. 6, on this surface. In coordinate system of Pluecker's conoid $R_K \equiv (\mathbf{e}_{1K}, \mathbf{e}_{2K}, \mathbf{e}_{3K})$ we can express position of any line of Pluecker's conoid as

$$\begin{aligned} y_K &= p \sin\vartheta \cos\vartheta, \\ z_k &= x_K \tan\vartheta, \end{aligned} \tag{2}$$

where parameter p is a distance between torsal planes, which are tangent planes to surface

Table 4: Displacements of bearing centres

Components	$\mathbf{u}_{A3}$	$\mathbf{u}_{B3}$	$\mathbf{u}_{A2}$	$\mathbf{u}_{B2}$
	[µm]			
Displacements under housing deformation				
x	-0,212	1,226	0,020	1,711
y	-0,221	-0,071	-0,203	-0,116
z	-0,720	-1,585	-0,659	-1,595
Displacements under bearing elastic deformation				
x	0,850	7,104	1,806	4,799
y	-1,142	-7,656	1,787	5,223
z	0,000	-0,560	0,000	-0,103
Total displacements				
x	0,638	8,330	1,826	6,510
y	-1,363	-7,726	1,584	5,107
z	-0,720	-2,145	-0,659	-1,698

of Pluecker's conoid at its top and bottom and simultaneously are perpendicular to axis y_K and ϑ is an angle which this line contains with axis x_K. First of all we have to establish of basic coordinate system of rotors R ≡ (**i**, **j**, **k**) in which the axis of male rotor o_3 in non-deformed ordering coalesces, Fig. 5, with axis z. The position of rotors in basic coordinate system R is determined with relation $\mathbf{r}_{O_3} = [0\ ,\ 0\ ,\ 0]^T$, $\mathbf{r}_{O_2} = [0\ ,\ a_w\ ,\ 0]^T$, $\nu_{o_3} \equiv \nu_{o_2} = [0\ ,\ 0\ ,\ 1]^\mathrm{T}$. After bearing displacements axes o_3, o_2 change into new positions o_3^Δ, o_2^Δ, which are determined, Fig. 5, with $\mathbf{r}_{O_3^\Delta} = \left[\Delta x_{O_3^\Delta}\ ,\ \Delta y_{O_3^\Delta}\ ,\ \Delta z_{O_3^\Delta}\right]^\mathrm{T}$, $\mathbf{r}_{O_2^\Delta} = \left[\Delta x_{O_2^\Delta}\ ,\ \Delta y_{O_2^\Delta}\ ,\ \Delta z_{O_2^\Delta}\right]^\mathrm{T}$,
$\nu_{o_3^\Delta} = \left[\cos\lambda_x^3\ ,\ \cos\lambda_y^3\ ,\ \cos\lambda_z^3\right]^\mathrm{T}$, $\nu_{o_2^\Delta} = \left[\cos\lambda_x^2\ ,\ \cos\lambda_y^2\ ,\ \cos\lambda_z^2\right]^\mathrm{T}$. Relative position of axes o_2^Δ and o_3^Δ is given, Fig. 7, by transversal **d** and angle Σ which are defined, Fig. 5, with relations

$$\mathbf{r}_{O_3^\Delta} + \mathbf{r}_{D_3} + \mathbf{d} + \mathbf{r}_{D_2} = \mathbf{r}_{O_2^\Delta}\ , \tag{3}$$

$$\cos\Sigma = \frac{\nu_{o_3^\Delta} \cdot \nu_{o_2^\Delta}}{\left|\nu_{o_3^\Delta}\right| \cdot \left|\nu_{o_2^\Delta}\right|}\ , \tag{4}$$

where $\mathbf{d} = d \cdot \mathbf{d}_0$ and unit vector $\mathbf{d}_0 = \dfrac{\nu_{o_3^\Delta} \times \nu_{o_2^\Delta}}{\left|\nu_{o_3^\Delta} \times \nu_{o_2^\Delta}\right|}$. The location of Pluecker's coordinate system has to fulfil the condition that transversal **d** lies on axis y_K, origin of coordinates Ω_K is in half of the length of transversal **d** and values of angles between x_K – coordinate and axes o_3^Δ and o_2^Δ are the same, i.e. $\vartheta_2 = -\vartheta_3 = \frac{\Sigma}{2}$. Location of axis of relative twist of both rotors is given

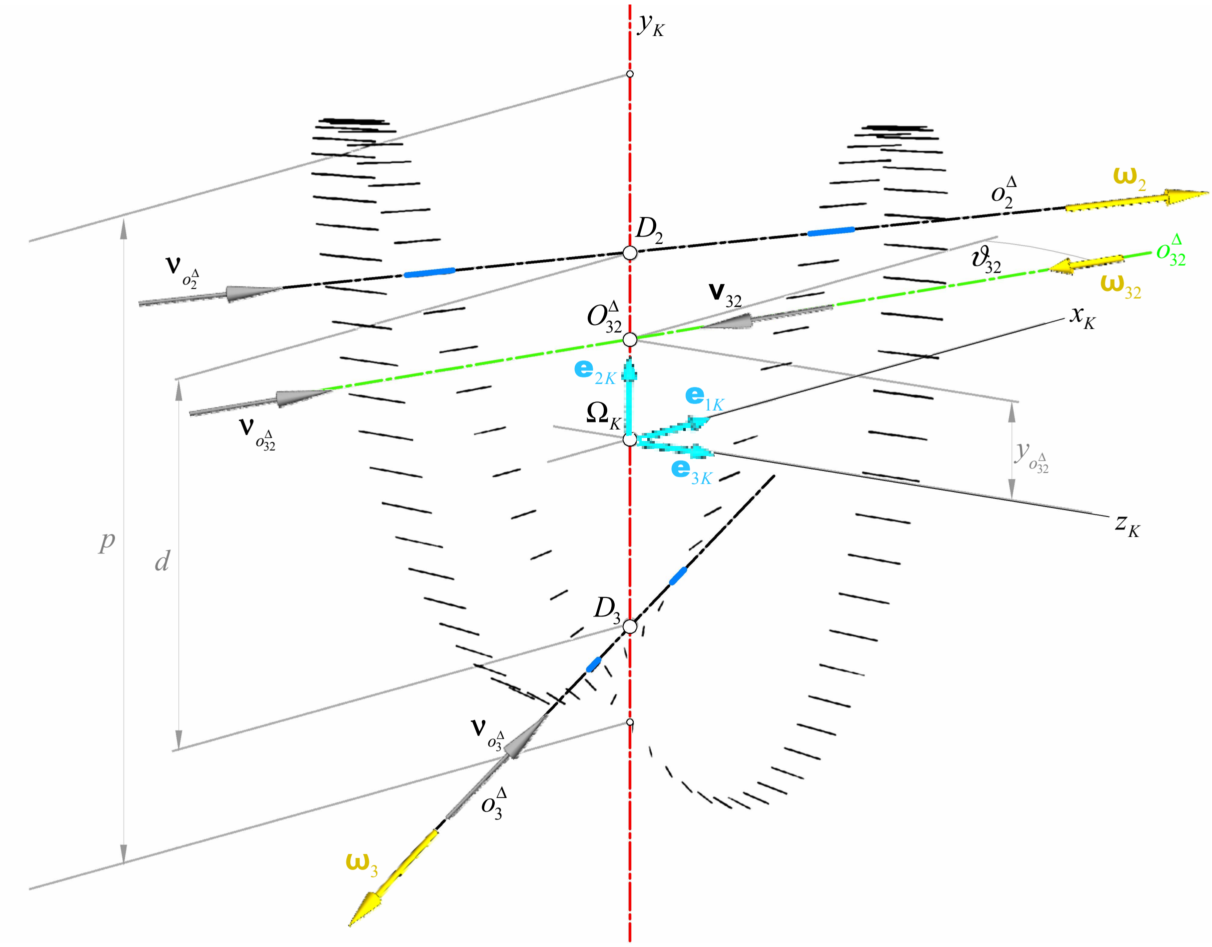

Fig 6: Pluecker's conoid and its coordinate system

with equation (2) where $\vartheta \equiv \vartheta_{32} = \vartheta_2 + \gamma_2$, $\tan\gamma_2 = \dfrac{\sin\Sigma}{\frac{1}{i_{32}} + \cos\Sigma}$ is angle, Fig. 6, between axis x_K and axis of relative twist o_{32}^Δ. Then the position of axis o_{32}^Δ in coordinate system of Pluecker's conoid R_K can be defined as

$$ {}_{R_K}\mathbf{r}_{O_{32}^\Delta} = \left[0\ ,\ y_{o_{32}^\Delta}\ ,\ 0\right]^T ,\quad {}_{R_K}\boldsymbol{\nu}_{o_{32}^\Delta} = \left[\cos\vartheta_{32}\ ,\ 0\ ,\ \sin\vartheta_{32}\right]^T . \tag{5} $$

For the expression of axis o_{32}^Δ in the basic space R the transformation relation $\mathbf{t}$: $R_K \to R$ is necessary to be used. This relation is given with transformation equation

$$ {}_R\mathbf{r}_{O_{32}^\Delta} = \mathbf{T}_{R_K R} \cdot {}_{R_K}\mathbf{r}_{O_{32}^\Delta} , \tag{6} $$

where

$$\mathbf{T}_{R_K R} = \mathbf{T}_{R_K R^{IV}}\ \mathbf{T}_{R^{IV} R^{III}}\ \mathbf{T}_{R^{III} R^{II}}\ \mathbf{T}_{R^{II} R^{I}}\ \mathbf{T}_{R^{I} R^{\Delta}}\ \mathbf{T}_{R^{\Delta} R} \tag{7}$$

is transformation matrix from space R_K into space R and $\mathbf{T}_{R_i R_j}$ denoting the transformation matrix from auxiliary space R_i to R_j. For transformation of unit vector $\nu_{o_{32}^{\Delta}}$ of axis relative twist o_{32}^{Δ} the using of rotation matrixes $\mathbf{S}_{R_i R_j}$ that create sub-matrixes of transformation matrices $\mathbf{T}_{R_i R_j}$, is sufficient. Position vectors ${}_R\mathbf{r}_{O_i^{\Delta}}$ of points O_i^{Δ}, Fig. 5, and unit vectors ${}_R\nu_{o_i^{\Delta}}$, i = 2, 3, eventually of point ${}_R O_{ij}^{\Delta}$ and ${}_R\nu_{o_{ij}^{\Delta}}$, i = 3, j = 2, are presented in Tab. 5 with their components in basic space R.

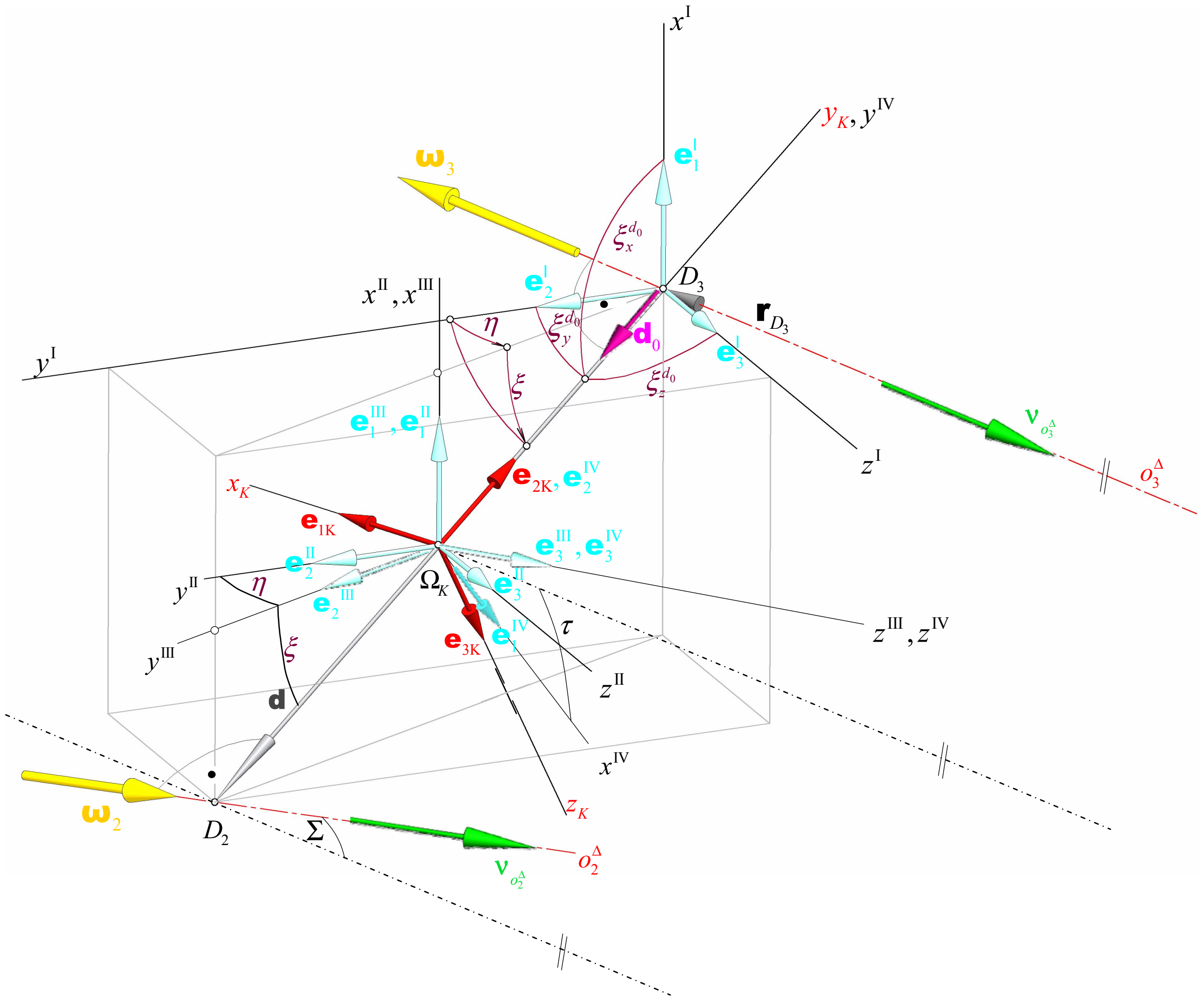

Fig 7: Pluecker's conoid location

Table 5: Components of position vectors and unit vectors

Components	$\mathbf{r}_{O_3^\Delta}$ [mm]	$\nu_{o_3^\Delta}$	$\mathbf{r}_{O_2^\Delta}$ [mm]	$\nu_{o_2^\Delta}$	$\mathbf{r}_{O_{32}^\Delta}$ [mm]	$\nu_{o_{32}^\Delta}$
x	0,0015062	0,00002894	0,0022079	0,00001736	2,2043258	0,00002368
y	-0,0020813	-0,00002394	85,0018713	0,00001306	39,3252740	-0,00000712
z	-0,0007200	0,99999999	-0,0006590	0,99999999	0,0	0,99999999

5. Consequences

In the first place the mutual force effect between of rotors was made. The relative force effect is given by difference of wrenches ρ_3 : $\mathbf{F}_3$, $\mathbf{M}_{o3}$ and ρ_2 : $\mathbf{F}_2$, $\mathbf{M}_{o2}$, Fig. 4, in the direction of axis o_{32}^Δ and in the directions perpendicular to this axis. In the case of non-deformed seating the axis o_{32}^Δ of relative screw motion, the twist degenerates into axis o_{32} of relative rolling. Relative force effect can to be express with relations

$$\begin{aligned} \mathbf{F}_{o_{32}^\Delta} &= \left[\left(\mathbf{F}_3 - \mathbf{F}_2 \right) \nu_{o_{32}^\Delta} \right] \nu_{o_{32}^\Delta} , \\ \mathbf{M}_{o_{32}^\Delta} &= \left[\left(\mathbf{M}_3 + \mathbf{r}_{O_3^\Delta} \times \mathbf{F}_3 - \left(\mathbf{M}_2 + \mathbf{r}_{O_2^\Delta} \times \mathbf{F}_2 \right) \right) \nu_{o_{32}^\Delta} \right] \nu_{o_{32}^\Delta} . \end{aligned} \tag{8}$$

Values of relative force effects in case of non-deformed seating of rotors are shown in Tab. 6. Values in case of deformed position of rotors are insignificantly different. In the second place the sensitivity analysis of mutual force effects from point of singular deformation of seating which is simulated by relative displacement and followed by relative angular displacements of male rotor axis o_3 with regard to female rotor axis o_2, was made. Sensitivity analysis was performed for functions $F_{O_{32}^\Delta}(\mathbf{p})$ and $M_{O_{32}^\Delta}(\mathbf{p})$ at point $\mathbf{p}_0 = [0,0,0,0,0]^{\mathrm{T}}$ in accordance with the relation

$$\frac{f(\mathbf{p}_0 + d \cdot \Delta\mathbf{p}_i) - f(\mathbf{p}_0)}{d \left| \Delta\mathbf{p}_i \right|} , \tag{9}$$

where $\Delta\mathbf{p}_i$ has all components of zero value except the i-component which is equal to i-component of vector $\Delta\mathbf{p} = [0{,}001,\ \ 0{,}001,\ \ 0{,}001,\ \ 1'',\ \ 0{,}5'']^{\mathrm{T}}$ .This vector was chosen. From the obtained values, Tab. 7, it is worth mentioning that both $F_{O_{32}^\Delta}$ and $M_{O_{32}^\Delta}$ are evidently more sensitive to turning axes o_3, in respect of axis o_2, angles $\Delta\xi$, $\Delta\varsigma$, then to their relative displacement.

Table 6: Relative force effects

Angle φ_3 [°]	0	18	36	54
$M_{o_{32}}$ [Nm]	55,10	56,96	54,48	56,61
$F_{o_{32}}$ [N]	-937,85	199,67	-1154,06	-1136,90

Table 7: Sensitivity of relative force effects to relative displacement of rotor axes

Parameter	$d = 10^{-6}$	$d = 10^{-8}$	$d = 10^{-10}$
Force sensitivity $F_{O_{32}^{\Delta}}$			
Δx	$0{,}00323 \cdot 10^{9}$	$0{,}00323 \cdot 10^{11}$	$0{,}00323 \cdot 10^{13}$
Δy	$0{,}00323 \cdot 10^{9}$	$0{,}00323 \cdot 10^{11}$	$0{,}00323 \cdot 10^{13}$
Δz	$0{,}00323 \cdot 10^{9}$	$0{,}00323 \cdot 10^{11}$	$0{,}00323 \cdot 10^{13}$
Δξ	$0{,}76914 \cdot 10^{9}$	$0{,}76914 \cdot 10^{11}$	$0{,}76914 \cdot 10^{13}$
Δζ	$1{,}33220 \cdot 10^{9}$	$1{,}33219 \cdot 10^{11}$	$1{,}33219 \cdot 10^{13}$
Moment sensitivity $M_{O_{32}^{\Delta}}$			
Δx	$-0{,}02286 \cdot 10^{8}$	$-0{,}02284 \cdot 10^{10}$	$-0{,}02284 \cdot 10^{12}$
Δy	$-0{,}02281 \cdot 10^{8}$	$-0{,}02284 \cdot 10^{10}$	$-0{,}02284 \cdot 10^{12}$
Δz	$-0{,}02284 \cdot 10^{8}$	$-0{,}02284 \cdot 10^{10}$	$-0{,}02284 \cdot 10^{12}$
Δξ	$-5{,}43900 \cdot 10^{8}$	$-5{,}43899 \cdot 10^{10}$	$-5{,}43899 \cdot 10^{12}$
Δζ	$-9{,}42062 \cdot 10^{8}$	$-9{,}42062 \cdot 10^{10}$	$-9{,}42062 \cdot 10^{12}$

Angle $\Delta\xi$ lies in plane parallel to coordinate plane *xy* and angle $\Delta\varsigma$ in plane perpendicular to coordinate plane *xy*. The change of the curve contact into the point contact, under the same force operation, causes that the force transformation between both rotors take place at this contact point and no at the curve. This fact is more important then the negligible difference between transmitted force effects. Normal force at general contact point L_i between tooth surfaces, that is evoked by transmition of torsion moment which is created by component of moment $\mathbf{M}_{32}$ into direction of axis o_{32}^{Δ}, is given with relation

$$N = \frac{M_{o_{32}^{\Delta}}}{\sum_{i=1}^{n} \left(x_i \; \mathbf{n}_{oi} \cdot \mathbf{j} - y_i \; \mathbf{n}_{oi} \cdot \mathbf{i} \right)}, \tag{10}$$

where x_i, y_i are coordinates of contact point L_i and $\mathbf{n}_{oi}$ is unit vector of normal in this point. The distribution of normal forces along the contact curve on condition that contact of tooth surfaces takes place in each point of contact curve is presented in Fig. 8. In case of the deformed position of rotors, where the contact takes place at the point, value of normal force is given by formula (10) for $i = k$, where k determines the single contact point L_k. The value of normal forces in both cases is at rate 1:86. Approximately it is possible to say that the simulation in case of contact stress is similar.

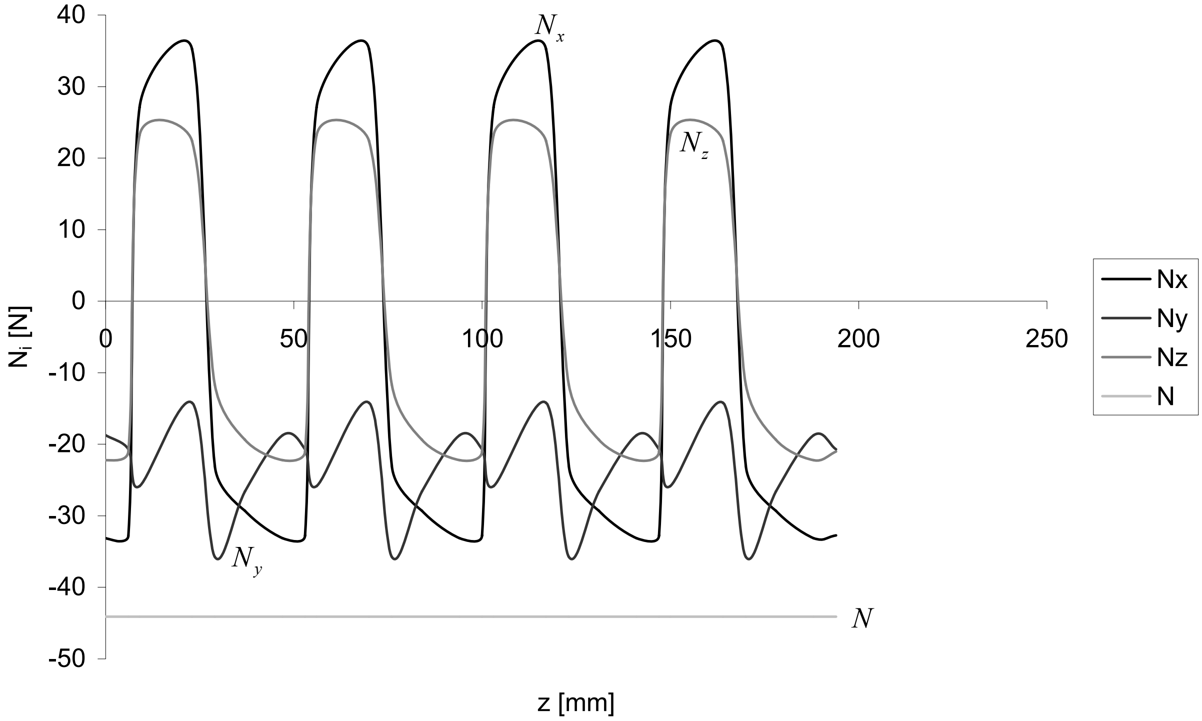

Fig 8: Distribution of normal forces along the contact line

Table 8: Normal force at isolated contact point

Components	**N** [N]
x	-1308,86
y	-3464,27
z	-793,75
Value	3787,39

Further, important consequence of change of the place of contact point is the change of gear ratio, which is undesirable from dynamic point of view.

6. Conclusion

The displacement of screw machine housing at places of rotor seating, which is caused by the deformation of housing and bearings under the operation of the force field, was solved. This displacement changes the parallel ordering of rotors into the spatial position. The original contact curve between tooth surfaces changes into the point contact, which changes the value of the normal force at the contact point. The ratio of values of normal forces at the general point of contact curve and at separated point is 1:86. The essential increases of the normal force at the separated contact point in the case of deformed rotor seating with regard to normal force at general point of contact curve in case of non-deformed, parallel, position of rotors, is the consequence of this change. Deformation of the machine housing was solved only for force load. It is possible to say that the deformations under the influence of the temperature field [4] are larger then the deformation under the influence of the force field. It is problem future solution. The most important is to ascertainment that any small deflection of rotors position evokes a large change in the mesh situation.

Acknowledgment
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