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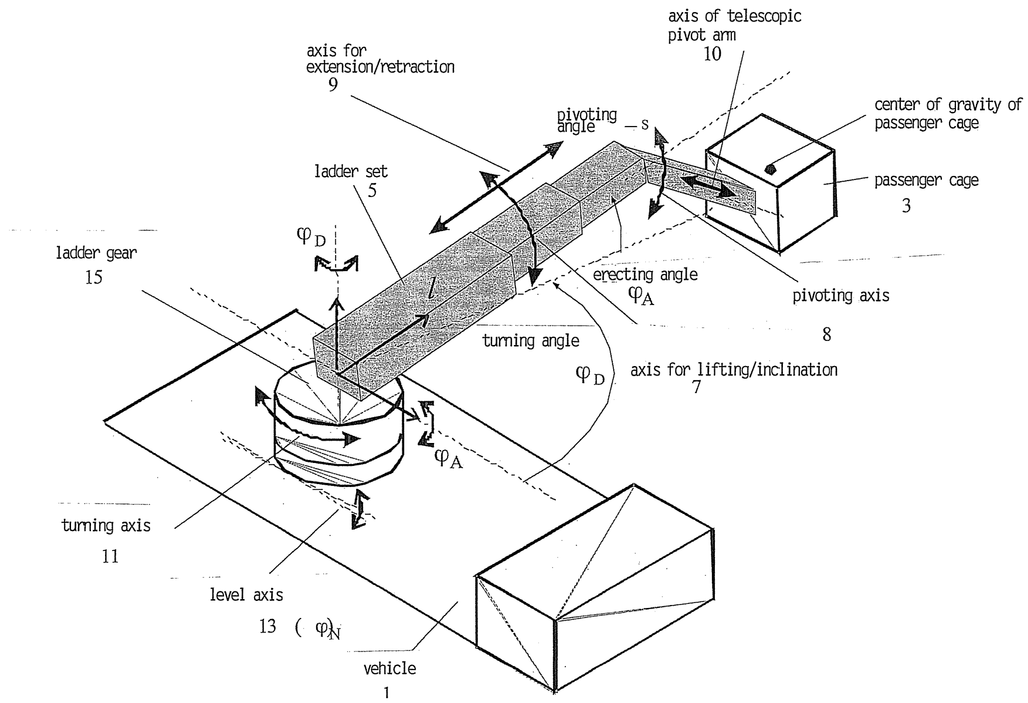
(54) **Turntable ladder**

(57) Turntable ladder, telescopic mast platform or similar, with a telescoping ladder set (5) or telescopic mast, and possibly, a passenger cage (3) attached thereto, said turntable ladder or telescopic mast comprising a control for the movement of the ladder parts or telescopic mast parts, which is contrived in such a way that when the turntable ladder or telescopic mast platform is operated, oscillations in the ladder parts or telescopic mast parts are suppressed in that at least one of the measured values, i.e. bending of the ladder set or telescopic mast in the horizontal or vertical directions, erection angle, angle of rotation, extension length and torsion of the ladder set or telescopic mast, is fed back via a controller to the control values for the drives, characterised in that attached to the ladder set or telescopic mast and/or to the passenger cage there are inertial sensors for detecting the bending state of the ladder set or telescopic mast.

Fig.1



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Description

[0001] The present invention concerns a turntable ladder, a telescopic platform or similar, with a telescoping ladder set or telescopic mast and, possibly, a passenger cage attached thereto, as per the preamble of claim 1.

[0002] Specifically, the invention concerns a turntable ladder, for example a fire-fighting ladder with a bendable articulated arm, or a similar system, such as articulated or telescopic platforms and aerial rescue equipment. These systems are, in general, mounted on a vehicle such that they are rotatable and erectable, and may be provided with a bendable articulated arm which may, additionally, be telescopeable with another axis. The control device is a continuous path control system which moves the passenger cage or lifting platform along a predetermined path in the operating area of the turntable ladder or lifting platform. Oscillations and pendulum movements by the passenger cage and lifting platform are actively dampened.

[0003] Control devices for turntable ladders, elevated platforms and similar are disclosed in DE 100 16 136 C2 and DE 100 16 137 C2, for example. Oscillations in the ladder elements can be suppressed if at least one value of the ladder set is fed back, via a controller, to the drive values for the drives. A pre-control device represents the ideal movement of the ladder in a dynamic model based on differential equations, and calculates ideal control values for the drives of the ladder elements, to enable essentially oscillation-free motion of the ladder. DE 10 2005 042 721 A1 discloses such a control device for a turntable ladder which, at the end of its ladder set, is provided with an articulated arm to which a passenger cage is attached. Its dynamic characteristics are included in the dynamic model used to represent the characteristics, thus allowing appropriate configuration of the control device.

[0004] Prior art articulated ladders or similar are hydraulically or electro-hydraulically controlled by hand-operated levers. In the case of the purely hydraulic control device, the hand-operated lever deflection is directly translated, via the hydraulic control circuit, into a proportional control signal for the control block, which is contrived as a proportional valve. Damping elements in the hydraulic control circuit can be used to render the movements less jerky and smoother in transition. These cannot, however, be satisfactorily adjusted to the entire operating area of extension length and erection angle. Furthermore, this often leads to strongly dampened adjustments with sluggish reactions.

[0005] Current continuous path control devices actively influence a counter-movement in the event of oscillation in the ladder set. However, the oscillation is only reconstructed from an expansion-measuring strip signal, and the model on which it is based only takes account of the fundamental oscillation components. Higher oscillation modes are not considered in the oscillation-damping arrangement according to DE 100 16 136 C2 and DE 100 16 137 C2. Furthermore, the reconstruction of the bending state is based solely on expansion-measuring strip signals and on a reconstruction derived from the pressure signal from the hydraulic unit. For the present case, involving simulation of harmonic oscillations, this is not always sufficient.

[0006] The task of this invention is, therefore, to create a turntable ladder, a telescopic mast platform or similar, according to the preamble of claim 1, in which the oscillation states of the ladder or the telescopic mast can be recorded and reconstructed more accurately, so that actively occurring oscillations (either during movement or when at rest, caused e.g. caused by wind or changes in load) can be dampened, or the ladder end with the passenger cage or work platform can be guided along a predetermined path. The aim is not only to enable compensation of fundamental oscillation, but also to effectively dampen the higher modes of oscillation.

[0007] According to the invention, this task is solved by a turntable ladder or telescopic mast platform with the features of claim 1.

[0008] According to the invention, inertial sensors are attached to the ladder set or telescopic mast and/or to the passenger cage for detecting the bending state of the ladder set or telescopic mast. The inertial sensors may be affixed either to the ladder set or the telescopic mast, to a passenger cage attached to the latter, or to both the ladder set or telescopic mast and the passenger cage.

[0009] A plurality of inertial sensors for measuring the angle speed in different spatial directions are preferably provided on the passenger cage and/or at the end of the ladder set or telescopic mast connected with the passenger cage.

[0010] According to another preferred form of embodiment, further inertial sensors are provided on the passenger cage and/or the corresponding end of the ladder set or telescopic mast for measuring acceleration in various spatial directions.

[0011] The use of, for example, a gyroscope platform on the top ladder part or telescopic mast part, or in the passenger cage, comprising up to three sensors in the Cartesian spatial directions for detecting angle speed, has proved particularly advantageous. This gyroscope platform can also be supplemented with three acceleration sensors in the corresponding spatial directions.

[0012] Other preferred embodiments of the invention result from sub-claims 4 to 9.

[0013] In particular, the turntable ladder or telescopic mast platform according to the present invention comprises a pre-control device which, when the passenger cage is operated, represents the ideal motion of the ladder or telescopic mast in a dynamic model, based on differential equations, and, using the dynamic model, calculates ideal control values for the drives of the ladder parts or telescopic mast parts for essentially oscillation-free movement of the ladder or the telescopic mast, said dynamic model simulating a mass distribution of the ladder set or telescopic mast.

[0014] As in the state of the art, the continuous path control with active oscillation damping according to the invention is also based on the basic idea of starting out by depicting the dynamic behaviour of the mechanical and hydraulic system of the turntable ladder or telescopic mast platform in a dynamic model based on differential equations.

[0015] In contrast to applications DE 100 16 136 C2 and DE 100 16 137 C2, the approach used for the dynamic model is not one based on an elastic multi-element model as an approximation for the distributed parametric model, but rather the distributed masses of the ladder set are modelled directly. In doing so, the mass of the passenger cage may still be taken as the point mass.

[0016] Also preferably, a path planning module is used to generate the path of movement of the ladder or telescopic mast in the operating area, and transmits the path of movement in the form of time functions for the passenger cage position, passenger cage speed, passenger cage acceleration, passenger cage jerking and, possibly, derivation of the passenger cage jerking, to a pre-control block which controls the drives of the ladder parts or the telescopic mast parts.

[0017] An example of a preferred embodiment of the invention will be described in more detail below with reference to the drawings, in which:

Figure 1 is a schematic diagram of the mechanical structure of an embodiment of a turntable ladder according to the present invention;

Figure 2 is a schematic diagram to explain the degrees of freedom of the system;

Figure 3 is a schematic diagram of the control circuit for controlling the movement of the turntable ladder of the invention according to a first embodiment;

Figure 4 shows a further control circuit for controlling the movement of a turntable ladder of the invention according to a second embodiment;

Figure 5 is a diagram to show intrinsic functions of the differential equation to describe the bending; and

Figures 6a and 6b are diagrams to show oscillation over time.

[0018] Whilst Figure 1 is a diagrammatic representation of the structure of the overall system, Figure 2 explains, by way of an example, the rotary motion of the turntable ladder according to the invention. The following representation of the invention relates by way of example only, but not in any limiting fashion, to a turntable ladder, and may also easily be used for a telescopic mast platform or similar, fitted with a telescoping mast. The individual parts of this telescopic mast then correspond to the ladder parts of the ladder set of the turntable ladder described here. Furthermore, the invention is not limited to a turntable ladder with a passenger cage, but can easily also be used on ladders or telescopic mast platforms without a passenger cage.

[0019] Fig. 3 shows a diagrammatic representation of a control circuit to control the movement of the turntable ladder presented here. In the model-based evaluation, the measured data from the gyroscope are initially corrected in relation to offset. In the model-based evaluation, the influence of gravity caused by the intrinsic weight of the ladder (during movement also) is calculated using the expansion-measuring strip signal. In the subsequent modal transformation, these signals are used to calculate the first two modes of intrinsic oscillation. These can then be compensatingly fed back in separated form via the controller feedback, and hence have an oscillation-damping effect. With respect to the previous state of the art one therefore achieves damping of both fundamental oscillation and first harmonic oscillation.

[0020] An alternative structure is shown in Fig. 4. In contrast to Fig. 3, however, only the fundamental oscillation is extracted from the sensor signals and the components of the higher modes are calculated via a model-based observer. This does not produce active suppression of first harmonic oscillation, but one can prevent the components of the higher modes from being coupled-in and having a destabilising effect on the vehicle via the feedback.
Once isolated, the fundamental oscillation is then fed back, with active damping effect, to the actuator input.

[0021] In both structures, it is very advantageous that the target trajectories are guided via a model-based pre-control device, and are thus adjusted to the dynamics of the system. This means generation of oscillation by the guide values of the system can be prevented. Contrary to the controls in DE 100 16 136 C2 and DE 100 16 137 C2, this method can be used for the generally non-linear case presented here.

[0022] This will now be explained by way of example for erection and inclination. The procedure can be directly transferred to the direction of rotation, as the influence of gravity is ignored for the consideration of the dynamic behaviour of the ladder. For the design of the pre-control, reference is again made to a model with concentrated parameters. The movement equations for the erection/inclination direction are as follows:

$$(I) \qquad \ddot{\varphi}_A = -\frac{1}{\tau_A}\dot{\varphi}_A + \frac{k_A}{\tau_A}u$$

$$(II) \qquad 0 = m_1\ddot{v}_z + m_1 L\ddot{\varphi}_A + d_{44}\dot{v}_z + c_v v_z + \frac{\left(L\dot{\varphi}_D + \dot{v}_y\right)^2}{2L}\sin\left(2x_1(t) + \frac{2}{L}x_3(t)\right) \qquad (1)$$

Key:

[0023]

$L(t)$... ladder length, parameter which changes over time
m_1... moving mass (dynamic component of total mass consisting of ladder set, possibly articulated part, plus passenger cage or elevated platform)
$c_v(L(t))$... rigidity as function of ladder length
$d_{44}(L(t))$... damping coefficient of ladder as function of ladder length
τ_A... time constant of hydraulic drive
k_A... amplification factor of hydraulic drive
$\varphi_D(t)$... speed of rotation, parameter which changes over time
$\dot{v}_y(t)$... deflection at ladder end in horizontal direction, parameter which changes over time

[0024] The model equations according to equation 1 are now converted to the generally non-linear state.

$$\begin{aligned}\dot{\underline{x}}(t) &= f\left(\underline{x}(t), u(t)\right) \\ y &= g\left(\underline{x}(t)\right)\end{aligned}, \text{ mit } \underline{x}(t) = \begin{bmatrix}\varphi_A(t) \\ \dot{\varphi}_A(t) \\ v_z(t) \\ \dot{v}_z(t)\end{bmatrix} \text{ und } u(t) = \dot{\varphi}_{A,Soll} \qquad (2)$$

[0025] The actuator input is the voltage across the proportional valve of the hydraulic system u(t), which may be interpreted as the target speed $\dot{\varphi}_{A,Soll}$. Eq. 1 thus yields the following non-linear equation of state with the output equation for the passenger cage position, taking account of bending:

$$\dot{\underline{x}}(t) = \begin{bmatrix} x_2(t) \\ -\frac{1}{\tau_A}x_2(t) + \frac{k_A}{\tau_A}u(t) \\ x_4(t) \\ \frac{L}{\tau_A}x_2(t) - \frac{c_v}{m_1}x_3(t) - \frac{d_{44}}{m_1}x_4(t) - \frac{\left(L\dot{\varphi}_D + \dot{v}_y\right)^2}{2L}\sin\left(2x_1(t) + \frac{2}{L}x_3(t)\right) - \frac{Lk_A}{\tau_A}u(t)\end{bmatrix} \qquad (3)$$

$$y(t) = x_1(t) + \sin\left(\frac{x_3(t)}{L}\right)$$

For the continuing system analysis, the relative degree of the system with regard to the chosen output is determined. The relative degree of $y(t)$ from eq. (3) equals 2. This is smaller than the system order (n = 4). Hence a differentially flat input with relative degree $r = 4$ is selected:

$$z(t) = x_1(t) + \frac{x_3(t)}{L} \approx y(t) \ \ \forall \ \frac{x_3(t)}{L} \leq 0{,}05 \qquad (4)$$

[0026] As it corresponds in a first approximation to the real control value (passenger cage position taking account of bending), there is no need to solve the remaining dynamics for generating reference trajectories.

[0027] The flatness-based analysis and design according to Rothfuß R.: Anwendung der flachheitsbasierten Analyse und Regelung nichtlinearer Mehrgrößensysteme, VDI-Verlag, 1997, are fully taken into account.

[0028] If one assumes $\dot{\varphi}_D = 0$ and $\dot{v}_y = 0$, based on the flat ouput of the passenger cage position, this yields the following parametrisation:

$$\begin{aligned}
z(t) &= x_1(t) + \frac{x_3(t)}{L} \\
\dot{z}(t) &= x_2(t) + \frac{x_4(t)}{L} \\
\ddot{z}(t) &= -\frac{c_v x_3(t)}{m_1 L} \\
\dddot{z}(t) &= -\frac{c_v x_4(t)}{m_1 L} \\
\ddddot{z}(t) &= -\frac{c_v}{\tau_A m_1^2 L}\left(m_1 L x_2(t) - \tau_A c_v x_3(t) - m_1 L k_A u(t)\right)
\end{aligned} \qquad (5)$$

[0029] The new system input is designated by $v(t) = \ddddot{z}(t)$ and it follows that the inverse control law for the pre-control is:

$$u(t) = \frac{1}{c_v k_A}\left(c_v \dot{z}_{ref}(t) + c_v \tau_A \ddot{z}_{ref}(t) + m_1 \dddot{z}_{ref}(t) + \tau_A m_1 v(t)\right) \qquad (6)$$

[0030] Using target trajectories over time for the passenger cage position and its derivations as input information, this allows the generation of an ideal control value for the valve position, without intrinsic oscillations being triggered when the ladder is moved. Remaining oscillations occur as a result of model inaccuracies and external factors (loading/unloading passenger cage, wind) and are suppressed via the feedback.

[0031] In the case of the structure of Fig. 3, feedback is achieved via a modal breakdown of the measured signals from the expansion-measuring strip and the gyroscope, plus feedback of the separated oscillation signals.

[0032] Modelling as a distributed mass for the ladder set and as a point mass for the passenger cage at the end of the ladder set means that the boundary conditions of the dynamics of the concentrated mass must be met. Although the oscillation of the ladder in the vertical plane is considered (the latter may be inclined by a certain erection angle), the influence of gravity for the concentrated mass is ignored as the mathematical model for small angles may be assumed to be linear and the stationary solution to the problem takes account of the influence of gravity. For the task of oscillation damping, this influence can, therefore, basically be eliminated from the outset. The ladder set is moved in the plane of the rotary movement through a moment M(t) at z = 0 of the ladder set (Fig. 2). L is the length of the ladder, θ(t) is the angle of rotation. w(z,t) is the bending. M_p and J_p are the mass of the passenger cage, and possibly the articulated arm, or the moment of inertia of the passenger cage converted into the moment of inertia relative to the centre of the gravity of the point mass. Assuming that the angle speed $\dot{\theta}(t)$ is small, and that Coriolis forces may be ignored, the ladder set can be described as a distributed mass using a Bernoulli bending beam using the following partial differential equation, with, in all acceleration terms **designated by the second derivation after time,** the rotation of the ladder set around the angle of rotation θ(t) being additionally taken into account:

$$EI\frac{\partial^4 w(z,t)}{\partial z^4} + \rho S\frac{\partial^2\left[\theta(t)z + w(z,t)\right]}{\partial t^2} = 0, \quad z \in (0,L),\ t > 0, \qquad (7)$$

$$w(0,t) = 0,\ t > 0, \qquad (8)$$

$$\frac{\partial w(0,t)}{\partial z} = 0,\ t > 0. \qquad (9)$$

$$-EI\frac{\partial^2 w(l,t)}{\partial z^2} = J_p\frac{d^2}{dt^2}\left(\theta(t) + \frac{\partial w(L,t)}{\partial z}\right),\ t > 0, \qquad (10)$$

$$EI\frac{\partial^3 w(L,t)}{\partial z^3} = M_p\frac{d^2}{dt^2}\left(\theta(t)L + w(L,t)\right),\ t > 0. \qquad (11)$$

[0033] Eq. (7) is the partial differential equation describing the bending. E is the elasticity module, I is the moment of inertia of area of the ladder set, ρ is the density, S is the (equivalent) cross-sectional area of the ladder set.

[0034] Eq.(8)-(9) are the boundary conditions corresponding to a fixed beam end at the start of the ladder set at z = 0.

[0035] Eq.(10) and (11) are the boundary conditions corresponding to the transition condition between distributed and concentrated mass, with eq.(10) describing the balance of the moments and eq.(11) the balance of the forces.

[0036] For the purpose of simplification, the following variable, describing the movement of individual points of the ladder set in the inertial area, is introduced:

$$V(z,t) \triangleq \theta(t)z + w(z,t)$$

[0037] Thus the system according to equations 7-11 may be described as

$$EI\frac{\partial^4 V(z,t)}{\partial z^4} + \rho S\frac{\partial^2 V(z,t)}{\partial t^2} = 0, \qquad (12)$$

$$V(0,t) = 0, \qquad (13)$$

$$\frac{\partial V(0,t)}{\partial z} = \theta(t), \qquad (14)$$

$$-EI\frac{\partial^2 V(l,t)}{\partial z^2} = J_p \frac{d^2}{dt^2}\left(\frac{\partial V(L,t)}{\partial z}\right), \quad (15)$$

$$EI\frac{\partial^3 V(l,t)}{\partial z^3} = M_p \frac{d^2 V(L,t)}{dt^2}. \quad (16)$$

[0038] To simplify, the following is introduced as the input value:

$$u(t) \stackrel{\Delta}{=} \theta(t) = \frac{\partial V(0,t)}{\partial z}. \quad (17)$$

[0039] The dynamics of the drive system are not taken into account. From the above input value, the moment M(t) can be calculated immediately according to the following context:

$$M(t) = J_h \frac{d^2\theta(t)}{dt^2} - EI\frac{\partial^2 w(0,t)}{\partial z^2}, \quad (18)$$

J_h is the moment of inertia of the ladder gear (15).

[0040] The solution according to eq. (12)-(16) can be shown in the following form

$$V(z,t) \stackrel{\Delta}{=} V_H(z,t) + V_I(z,t), \quad (19)$$

where $V_I(z,t)$ is that part of the general solution V(z,t) which need only satisfy the inhomogeneous boundary conditions according to eq. (13)-(16), whereas $V_H(z,t)$ must satisfy both the homogeneous boundary conditions and eq.(12). The following is selected as an approach for $V_I(z,t)$:

$$V_I(x,t) \stackrel{\Delta}{=} f(z)u(t) \text{ where}$$
$$f(z) \stackrel{\Delta}{=} A + Bz + Cz^2 + Dz^3 + Ez^4 + Fz^5,\ z \in [0,L]$$

[0041] From (13) and (14) it follows:

$$A = 0,\ B = 1.$$

[0042] To satisfy boundary conditions (15) and (16), the following equation system must be solved:

$$\begin{bmatrix} 2 & 6L & 12L^2 & 20L^3 \\ 2L & 3L^2 & 4L^3 & 5L^4 \\ 0 & 6 & 24L & 60L^2 \\ L^2 & L^3 & L^4 & L^5 \end{bmatrix} \begin{bmatrix} C \\ D \\ E \\ F \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 0 \\ -L \end{bmatrix}. \qquad (20)$$

[0043] Eq. (20) has a clear-cut solution:

$$C = -4L^{-1}, D = 6L^{-2}, E = -4L^{-3}, F = L^{-4}$$

[0044] The solution approach used in eq. (19) is now used in eq. (12)-(16). This yields the following equation system:

$$EI\frac{\partial^4 V_H(z,t)}{\partial z^4} + \rho S\frac{\partial^2 V_H(z,t)}{\partial t^2} = \\ = -\left[EI\frac{\partial^4 V_I(z,t)}{\partial z_1^4} + \rho S\frac{\partial^2 V_I(z,t)}{\partial t^2}\right], \qquad (21)$$

$$V_H(0,t) = 0, \qquad (22)$$

$$\frac{\partial V_H(0,t)}{\partial z} = 0, \qquad (23)$$

$$\frac{\partial^2 V_H(L,t)}{\partial z^2} - \mu\frac{d^2}{dt^2}\left(\frac{\partial V_H(L,t)}{\partial z}\right) = 0, \qquad (24)$$

$$\frac{\partial^3 V_H(L,t)}{\partial z^3} - \kappa\frac{d^2 V(L,t)}{dt^2} = 0. \qquad (25)$$

[0045] The following substitution was used for simplification:

$$\mu \triangleq -\frac{J_p}{EI}, \ \kappa \triangleq \frac{M_p}{EI}. \qquad (26)$$

[0046] The following approach is used for the homogeneous solution:

$$V_H(z,t) \triangleq Z(z)T(t). \qquad (27)$$

[0047] If (27) is used in the homogeneous part of eq. (21), one obtains:

$$EI\,Z^{(IV)}(z)T(t) + \rho S Z(z)\ddot{T}(t) = 0. \qquad (28)$$

[0048] In the following, it is assumed that a set of functions

$$\{Z_n(z)\}_{n\geq 1},\ \{T_n(z)\}_{n\geq 1}$$

can meet eq.(28) and the boundary conditions eq. (22)-(25). Eq.(28) can be written as

$$\frac{Z_n^{(IV)}(z)}{Z_n(z)} = -\eta\frac{\ddot{T}_n(t)}{T_n(t)} \triangleq \lambda_n, \qquad (29)$$

where

$$\eta \triangleq \rho S/EI$$

λ_n is the related intrinsic value. From (29), one can then formulate the following differential equation for the amplitudes of time functions $T_n(t)$.

$$\ddot{T}_n(t) + \omega_n^2 T_n(t) = 0, \qquad (30)$$

where

$$\omega_n = \sqrt{\lambda_n/\eta}$$

is to the intrinsic value λ_n.
With (29) and use of approach (27) in (22)-(25), one can formulate the following boundary value problem for the location-dependent intrinsic functions $Z_n(z)$.

$$Z_n^{(IV)} - \lambda_n Z_n = 0, \qquad (31)$$

$$T_n Z_n(0) = 0, \qquad (32)$$

$$T_n Z_n'(0) = 0, \qquad (33)$$

$$T_n Z_n''(L) = \mu \ddot{T}_n Z_n'(L), \tag{34}$$

$$T_n Z_n'''(L) = \kappa \ddot{T}_n Z_n(L). \tag{35}$$

[0049] With eq. (24) the remaining time functions $T_n(t)$ in (34)-(35) can be eliminated. From boundary conditions (32)-(35), this gives:

$$Z_n(0) = 0, \tag{36}$$

$$Z_n'(0) = 0, \tag{37}$$

$$Z_n''(L) + \lambda_n \left(\frac{\mu}{\eta}\right) Z_n'(L) = 0, \tag{38}$$

$$Z_n'''(L) + \lambda_n \left(\frac{\kappa}{\eta}\right) Z_n(L) = 0. \tag{39}$$

[0050] The solution leads to the following relationships. As the characteristic polynome (31) has the roots,

$$\left\{-\sqrt[4]{\lambda_n},\ \sqrt[4]{\lambda_n},\ -j\sqrt[4]{\lambda_n},\ j\sqrt[4]{\lambda_n}\right\}$$

the general solution can be written in the following form.

$$\begin{aligned} Z_n(z) = A_n \cosh\left(\sqrt[4]{\lambda_n} z\right) + B_n \sinh\left(\sqrt[4]{\lambda_n} z\right) + \\ + C_n \cos\left(\sqrt[4]{\lambda_n} z\right) + D_n \sin\left(\sqrt[4]{\lambda_n} z\right). \end{aligned} \tag{40}$$

[0051] The boundary conditions (36)-(37) at the boundary z=0 immediately give

$$C_n = -A_n,\ D_n = -B_n$$

and:

$$\begin{aligned} Z_n(z) &= A_n\left[\cosh\left(\sqrt[4]{\lambda_n}z\right)-\cos\left(\sqrt[4]{\lambda_n}z\right)\right]+ \\ &+ B_n\left[\sinh\left(\sqrt[4]{\lambda_n}z\right)-\sin\left(\sqrt[4]{\lambda_n}z\right)\right] \end{aligned} \qquad (41)$$

The boundary conditions (38)-(39) at boundary z=L lead to the following linear algebraic equation system

$$\begin{aligned} A_n\sqrt{\lambda_n}\,(\cosh+\cos)+B_n\sqrt{\lambda_n}\,(\sinh+\sin)+ \\ +A_n\sqrt[4]{\lambda_n}\lambda_n\left(\frac{\mu}{\eta}\right)(\sinh+\sin)+ \\ +B_n\sqrt[4]{\lambda_n}\lambda_n\left(\frac{\mu}{\eta}\right)(\cosh-\cos)=0, \\ A_n\left(\sqrt[4]{\lambda_n}\right)^3(\sinh-\sin)+B_n\left(\sqrt[4]{\lambda_n}\right)^3(\cosh+\cos)+ \\ +A_n\left(\frac{\kappa}{\eta}\right)\lambda_n\,(\cosh-\cos)+B_n\left(\frac{\kappa}{\eta}\right)\lambda_n\,(\sinh-\sin)=0. \end{aligned} \qquad (42)$$

[0052] To simplify, the argument $\sqrt[4]{\lambda_n}L$ of the trigonometric and hyperbolic functions has been omitted. The homogeneous system (42) has non-trivial solutions if the determinant of the coefficients is 0.

$$\begin{aligned} &\underbrace{\left[\sqrt{\lambda_n}\,(\cosh+\cos)+\sqrt[4]{\lambda_n}\lambda_n\left(\frac{\mu}{\eta}\right)(\sinh+\sin)\right]}_{\triangleq A_{11}(\lambda_n)}\times \\ &\times\left[\left(\sqrt[4]{\lambda_n}\right)^3(\cosh+\cos)+\left(\frac{\kappa}{\eta}\right)\lambda_n\,(\sinh-\sin)\right]- \\ &-\underbrace{\left[\sqrt{\lambda_n}\,(\sinh+\sin)+\sqrt[4]{\lambda_n}\lambda_n\left(\frac{\mu}{\eta}\right)(\cosh-\cos)\right]}_{\triangleq A_{12}(\lambda_n)}\times \\ &\times\left[\left(\sqrt[4]{\lambda_n}\right)^3(\sinh-\sin)+\left(\frac{\kappa}{\eta}\right)\lambda_n\,(\cosh-\cos)\right]=0 \end{aligned}$$

[0053] This transcendent function can only be solved numerically in relation to intrinsic values λ_n. (the figure $\lambda = 0$ is a trivial solution to the problem, and is therefore not an intrinsic value). The intrinsic function to intrinsic value λ_n can now be described as

$$Z_n(z) = -\frac{A_{12}(\lambda_n)}{A_{11}(\lambda_n)}\left[\cosh\left(\sqrt[4]{\lambda_n}z\right) - \cos\left(\sqrt[4]{\lambda_n}z\right)\right] + \\ + \left[\sinh\left(\sqrt[4]{\lambda_n}z\right) - \sin\left(\sqrt[4]{\lambda_n}z\right)\right].$$

[0054] In Fig. 5, the first three intrinsic functions of the problem are shown by way of example in standardised form (Z_{i0}, i=1,2,3). Based on these results, one then derives the modal representation of the distributed parametric system. The part of the solution which solves both the homogeneous boundary conditions and eq. (21) can now be described as

$$V_H(z,t) \triangleq \sum_{k=1}^{+\infty} V_{Hi}^*(t) Z_{k0}(z). \qquad (43)$$

[0055] If (43) is inserted in eq. (21), one obtains

$$\sum_{k=1}^{+\infty} V_{Hk}^*(t)\lambda_k Z_{k0}(z) + \eta \sum_{k=1}^{+\infty} \frac{d^2 V_{Hk}^*(t)}{dt^2} Z_{k0}(z) = \\ = -\sum_{k=1}^{+\infty} f_k^{(IV)*} Z_{k0}(z) u(t) - \eta \sum_{k=1}^{+\infty} f_k^* Z_{k0}(z) \frac{d^2 u(t)}{dt^2}, \qquad (44)$$

$f_k^*, f_k^{*(IV)}$ are the coefficients of

$$f(z) = \sum_{k=1}^{+\infty} f_k^* Z_{k0}(z), \quad f^{(IV)}(z) = \sum_{k=1}^{+\infty} f_k^{(IV)*} Z_{k0}(z).$$

With (44), all time modes (amplitudes of intrinsic functions) in the frequency range can be shown with the aid of the Laplace transform in the following form.

$$\hat{V}_{Hk}^*(s) = -\frac{f_k^* s^2 + \frac{1}{\eta} f_k^{(IV)*}}{s^2 + \omega_k^2}\hat{u}(s) + \\ + \frac{s}{s^2 + \omega_k^2} V_{Hk}^*(0) + \frac{1}{s^2 + \omega_k^2}\dot{V}_{Hk}^*(0). \qquad (45)$$

[0056] In the frequency range one therefore obtains with (19)

$$\hat{V}(z,s) = \hat{V}_H(z,s) + \hat{V}_I(z,s) = \sum_{k=1}^{+\infty} \hat{V}_{Hk}^{*}(s) Z_{k0}(z) + \\ + \left(z - 4L^{-1}z^2 + 6L^{-2}z^3 - 4L^{-3}z^4 + L^{-4}z^5\right)\hat{u}(s). \quad (46)$$

[0057] From here, N modes (i.e. the first N summands of infinite rows (45)-(46)) can be used for simulation purposes. For the following control design, the modal representation is selected as follows:

$$V_k^*(t) = V_{Hk}^*(t) + V_{Ik}^*(t),\ \ k \geq 1, \qquad (47)$$

where

$$V_{Ik}^*(t) = f_k^* u(t)$$

is determined from

$$V_I(z,t) = f(z)u(t)$$

[0058] With (44) and (47) one then obtains

$$\frac{d^2 V_k^*(t)}{dt^2} + \omega_k^2 V_k^*(t) = \left(\omega_k^2 f_k^* - \frac{f_k^{(IV)*}}{\eta}\right) u(t).$$

[0059] For the purposes of the example, only the first two modes are considered. Adding the state values

$$x_1(t) \stackrel{\Delta}{=} V_1^*(t),\ \ x_2(t) \stackrel{\Delta}{=} \dot{x}_1(t) = \dot{V}_1^*(t), \\ x_3(t) \stackrel{\Delta}{=} V_2^*(t),\ \ x_4(t) \stackrel{\Delta}{=} \dot{x}_3(t) = \dot{V}_2^*(t).$$

gives the representation of the state space

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 & 0 & 0 \\ -\omega_1^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\omega_2^2 & 0 \end{bmatrix}}_{\triangleq A} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + $$

$$+ \underbrace{\begin{bmatrix} 0 \\ \omega_1^2 f_1^* - \frac{f_1^{(IV)*}}{\eta} \\ 0 \\ \omega_2^2 f_2^* - \frac{f_2^{(IV)*}}{\eta} \end{bmatrix}}_{\triangleq B} u(t). \qquad (48)$$

[0060] Based on this representation, the controller design is now carried out. To this end, one considers the operating point

$$V_0(z) \equiv 0, \forall z \in [0, L]$$

[0061] For the technical implementation it has proven sufficient for the controller design to consider only the first two modes of the system, as the limit frequency of the hydraulic system is situated at about 3-4 Hz, although the 3rd mode is approx. 6.5 Hz. Hence the higher modes are ignored. To now stabilise the system (48) with 2 complex conjugate pole pairs with a state feedback, which lie on the imaginary axis, as there is no damping in the model presented, all state values x_1 to x_4 must be measureable. To this end, measured values are available from an expansion-measuring strip sensor on the lower ladder part, and a gyroscope at the top of the ladder. The idea now is to use these sensor values in an observer structure, which additionally brings together (i.e. merges) both measured values, to estimate what amplitude components the modes make up of the oscillation. The expansion-measuring strip sensor at installation position z=z1 delivers a bending value which can be described in the present notation as follows:

$$m_1(t) = \frac{\partial^2 w(z_1, t)}{\partial z^2} = \frac{\partial^2 V(z_1, t)}{\partial z^2}$$

[0062] The measured value of the gyroscope (installed at point z=z2) yields

$$m_2(t) = \frac{\partial^2 V(z_2, t)}{\partial z \partial t}.$$

[0063] If only 2 modes are considered, both measured values can be expressed via the state values as follows:

$$m_1(t) = \frac{\partial^2 V(z_1, t)}{\partial z^2} = \hat{x}_1(t) Z''_{10}(z_1) + \hat{x}_3(t) Z''_{20}(z_1),$$

$$m_2(t) = \frac{\partial^2 V(z_2,t)}{\partial z \partial t} = \hat{x}_2(t) Z'_{10}(z_2) + \hat{x}_4(t) Z'_{20}(z_2).$$

[0064] To reconstruct all state values, 2 other signals are required, which are obtained by integration or real differentiation.

$$\frac{dm_1(t)}{dt} = \frac{\partial^3 V(z_1,t)}{\partial z^2 \partial t} = \hat{x}_2(t) Z''_{10}(z_1) + \hat{x}_4(t) Z''_{20}(z_1),$$

$$\int_0^t m_2(\tau) d\tau = \frac{\partial V(z_2,t)}{\partial z} = \hat{x}_1(t) Z'_{10}(z_2) + \hat{x}_3(t) Z'_{20}(z_2).$$

[0065] The estimate of the mode amplitudes can then be obtained from the solution to the following algebraic equation system.

$$\begin{bmatrix} Z''_{10}(z_1) & 0 & Z''_{20}(z_1) & 0 \\ 0 & Z'_{10}(z_2) & 0 & Z'_{20}(z_2) \\ 0 & Z''_{10}(z_1) & 0 & Z''_{20}(z_1) \\ Z'_{10}(z_2) & 0 & Z'_{20}(z_2) & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \\ \hat{x}_4(t) \end{bmatrix} = \\ = \begin{bmatrix} m_1(t) \\ m_2(t) \\ dm_1(t)/dt \\ \int_0^t m_2(\tau) d\tau \end{bmatrix}. \qquad (49)$$

[0066] After inverting the matrix with the intrinsic functions Z, one obtains a direct functional relationship between the measured values at the expansion-measuring strip and the gyroscope, and the amplitudes for the first two modes. One can then go straight to designing a pole assignment controller.

$$u(t) = K \left[\hat{x}_1(t) \quad \hat{x}_2(t) \quad \hat{x}_3(t) \quad \hat{x}_4(t) \right]^T,$$

where the amplitude matrix is calculated from the determinant of

$$A - BK$$

by assigning the zero positions of the characteristic equation. Fig. 6a and 6b show, by way of example, the damping characteristics of the control. In Figure 6a, the bending b (L, t) is shown over time, Figure 6b shows the actuator value. In the case shown here, the control is turned on after ten seconds.

[0067] The alternative structure shown in Fig. 4 will now be explained below, where, in a model-based observer, the fundamental oscillation is extracted from the measured signals. This block shall now be described in more detail below.

[0068] The interference value observer for the sensor data merger from the gyroscope measurement at the cage fixation and the expansion-measuring strip at the fixing point of the ladder, should separate the fundamental oscillation of the bending oscillation from its dominant harmonics in order to exclude, as far as possible, any amplification of the harmonics in the feedback.

[0069] For the observer, simple oscillation differential equations are used for the model equation. As the gyroscope signal is overlain by a substantial offset, this influence is compensated by an integrator interference model in the model equations.

$$\begin{aligned} K_0\omega_0^2\ddot{\varphi}_A(t)+\ddot{v}_{0z}(t)+2D_0\omega_0\dot{v}_{0z}(t)+\omega_0^2 v_{0z} &= 0 \quad \ldots \quad \text{Grundwelle} \\ K_1\omega_1^2\ddot{\varphi}_A(t)+\ddot{v}_{1z}(t)+2D_1\omega_1\dot{v}_{1z}(t)+\omega_1^2 v_{1z} &= 0 \quad \ldots \quad \text{1. Oberwelle} \\ \ddot{\overline{v}}_z &= 0 \quad \ldots \quad \text{triviale Dynamik des Offset der} \\ & \qquad\quad\;\; \text{Gyroskopmessung } \left(\dot{\varphi}_A(t,L) \Box\, \dot{v}_z\right) \end{aligned} \tag{50}$$

[0070] (Translator's note: Grundwelle = "Fundamental oscillation", 1. Oberwelle = "First harmonic oscillation", triviale Dynamik des Offset der Gyroskopmessung = "Trivial dynamics of offset of gyroscope measurement")

[0071] Parameters ω_i, D_i and K_i are determined by experimental process analysis. In the state representation this then corresponds to:

$$\begin{aligned} \dot{\underline{x}}(t) &= \mathbf{A}\underline{x}(t)+\mathbf{b}u(t) \\ y &= \mathbf{C}\underline{x}(t) \end{aligned}, \text{ mit } \underline{x}(t)=\begin{bmatrix} v_{0z}(t) \\ \dot{v}_{0z}(t) \\ v_{1z}(t) \\ \dot{v}_{1z}(t) \\ \overline{v}(t) \end{bmatrix} \text{ und } u(t)=\ddot{\varphi}_A$$

with

$$\dot{\underline{x}}(t)=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\omega_0^2 & -2D_0\omega_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -\omega_1^2 & -2D_1\omega_1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}\underline{x}(t)+\begin{bmatrix} 0 \\ -K_0\omega_0^2 \\ 0 \\ -K_1\omega_1^2 \\ 0 \end{bmatrix}u(t) \tag{51}$$

$$y_m(t)=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 \end{bmatrix}\underline{x}(t) \Box \begin{bmatrix} \text{DMS} \\ \text{Gyroskop} \end{bmatrix}$$

[0072] The first component of the output vector corresponds to the DMS signal, the second component to the gyroscope measurement.

[0073] For the design of the observer one may select, for example, a method based on representation as observer normal form. The advantageous aspect is that simple design equations can then be derived for the observer feedback matrix $\underline{H}$ over the poles to be assigned $p_i, i \in \Box \wedge [1,5]$. After transformation to the observer normal form (2nd form) for multivariable systems, eq. 51 becomes

$$\mathbf{A}_{\text{BNF 2.Art}} = \begin{bmatrix} 0 & -\omega_0^{\,2} & 0 & 0 & 0 \\ 1 & -2D_0\omega_0 & 0 & 0 & 0 \\ 0 & \left(1-4D_0^{\,2}\right)\omega_0^{\,4} + 4D_0D_1\omega_0^{\,3}\omega_1 - \omega_0^{\,2}\omega_1^{\,2} & 0 & 0 & 0 \\ 0 & \left(4D_0 - 8D_0^{\,3}\right)\omega_0^{\,3} + \left(8D_0^{\,2}D_1\omega_1 - 2D_1\omega_1\right)\omega_0^{\,2} - 2D_0\omega_0\omega_1^{\,2} & 1 & 0 & -\omega_1^{\,2} \\ 0 & 0 & 0 & 1 & -2D_1\omega_1 \end{bmatrix}$$

$$\mathbf{b}_{\text{BNF 2.Art}} = \begin{bmatrix} -K_0\omega_0^{\,2} \\ 0 \\ -\left(\omega_1^{\,2} - \omega_0^{\,2} + 4D_0^{\,2}\omega_0 - 4D_0D_1\omega_0\omega_1\right)K_0\omega_0^{\,2} \\ 2\left(D_0\omega_0 - D_1\omega_1\right)K_0\omega_0^{\,2} \\ -K_0\omega_0^{\,2} - K_1\omega_1^{\,2} \end{bmatrix}$$

$$\mathbf{C}_{\text{BNF 2.Art}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\Rightarrow \mathbf{H}_{\text{BNF 2.Art}} = \begin{bmatrix} -\omega_0 + p_1p_2 & 0 \\ -2D_0\omega_0 - p_1 - p_2 & 0 \\ \left(1-4D_0^{\,2}\right)\omega_0^{\,4} + 4D_0D_1\omega_0^{\,3}\omega_1 - \omega_0^{\,2}\omega_1^{\,2} & -p_3p_4p_5 \\ \left(4D_0 - 8D_0^{\,3}\right)\omega_0^{\,3} + \left(8D_0^{\,2}D_1\omega_1 - 2D_1\omega_1\right)\omega_0^{\,2} - 2D_0\omega_0\omega_1^{\,2} & -\omega_1^{\,2} + p_3p_5 + p_3p_4 + p_4p_5 \\ 0 & -2D_1\omega_1 - p_3 - p_4 - p_5 \end{bmatrix} \quad (52$$

[0074] The observer is thus in a position to generate, using the interference-affected (by harmonic oscillation, etc.) measured signals from expansion-measuring strip and gyroscope, a reconstructed estimated signal for the fundamental oscillation, which then has a damping effect, via feedback, on the ladder oscillations.

[0075] As a general remark, it should be noted that all the approaches presented can be transferred in analog manner to the direction of rotation of the ladder.

Claims

1. Turntable ladder, telescopic mast platform or similar, with a telescoping ladder set and, possibly, a passenger cage attached thereto, said turntable ladder or telescopic mast comprising a control for the movement of the ladder parts or telescopic mast parts, which is contrived such that when the turntable ladder or telescopic mast platform are operated, oscillations in the ladder parts or telescopic mast parts are suppressed in that at least one of the measured values, i.e. bending of the ladder set or telescopic mast in the horizontal and vertical directions, erection angle, angle of rotation, extension length and torsion in the ladder set or telescopic mast is fed back via a controller to the control values for the drives, **characterised in that** attached to the ladder set or telescopic mast and/or to the passenger cage, there are inertial sensors for detecting the bending state of the ladder set or telescopic mast.

2. The turntable ladder or telescopic mast platform of claim 1, **characterised in that** a plurality of inertial sensors for measuring the angle speed in various spatial directions are provided on the passenger cage and/or at the end of the ladder set or telescopic mast to which the passenger cage is attached.

3. The turntable ladder or telescopic mast platform according to claim 2, **characterised in that** further inertial sensors for measuring acceleration in various spatial directions are provided on the passenger cage and/or at the end of the ladder set or telescopic mast to which the passenger cage is attached.

4. The turntable ladder or telescopic mast platform according to one of the previous claims, **characterised in that** expansion-measuring strip sensors for detecting the bending state of the ladder set or telescopic mast are attached to the ladder set or telescopic mast.

5. The turntable ladder or telescopic mast platform of claim 4, **characterised in that** the bending state of the ladder set or telescopic mast is reconstructed from the sensor signals provided by the inertial sensors and the expansion-measuring strips.

6. The turntable ladder or telescopic mast platform according to claim 5, **characterised in that** the result of the sensor data merger undergoes a modal transformation to calculate the first two modes of intrinsic oscillation in the ladder set or telescopic mast, which are fed back to the controller as a control value.

7. The turntable ladder or telescopic mast platform according to claim 5, **characterised in that** only the fundamental oscillation of the ladder set or telescopic mast is extracted from the result of the sensor data merger and this is fed back to the controller as a control value.

8. The turntable ladder or telescopic mast platform according to one of the previous claims, **characterised in that** a pre-control, which, when the passenger cage is operated, represents the ideal motion of the ladder or the telescopic mast in a dynamic model, based on differential equations, and calculates, from the dynamic model, ideal control values for the drives of the ladder parts or telescopic mast parts for essentially oscillation-free movement of the ladder or telescopic mast, said dynamic model representing a mass distribution of the ladder set or telescopic mast.

9. The turntable ladder or telescopic mast platform according to one of the previous claims, **characterised in that** a continuous path planning module is provided for generating the movement path of the ladder or telescopic mast in the working space, which gives the movement path in the form of time functions for the passenger cage position, passenger cage speed, passenger cage acceleration, passenger cage jerking and, possibly, deflection of the passenger cage jerking, to a pre-control block which controls the drives of the ladder parts or telescopic mast parts.

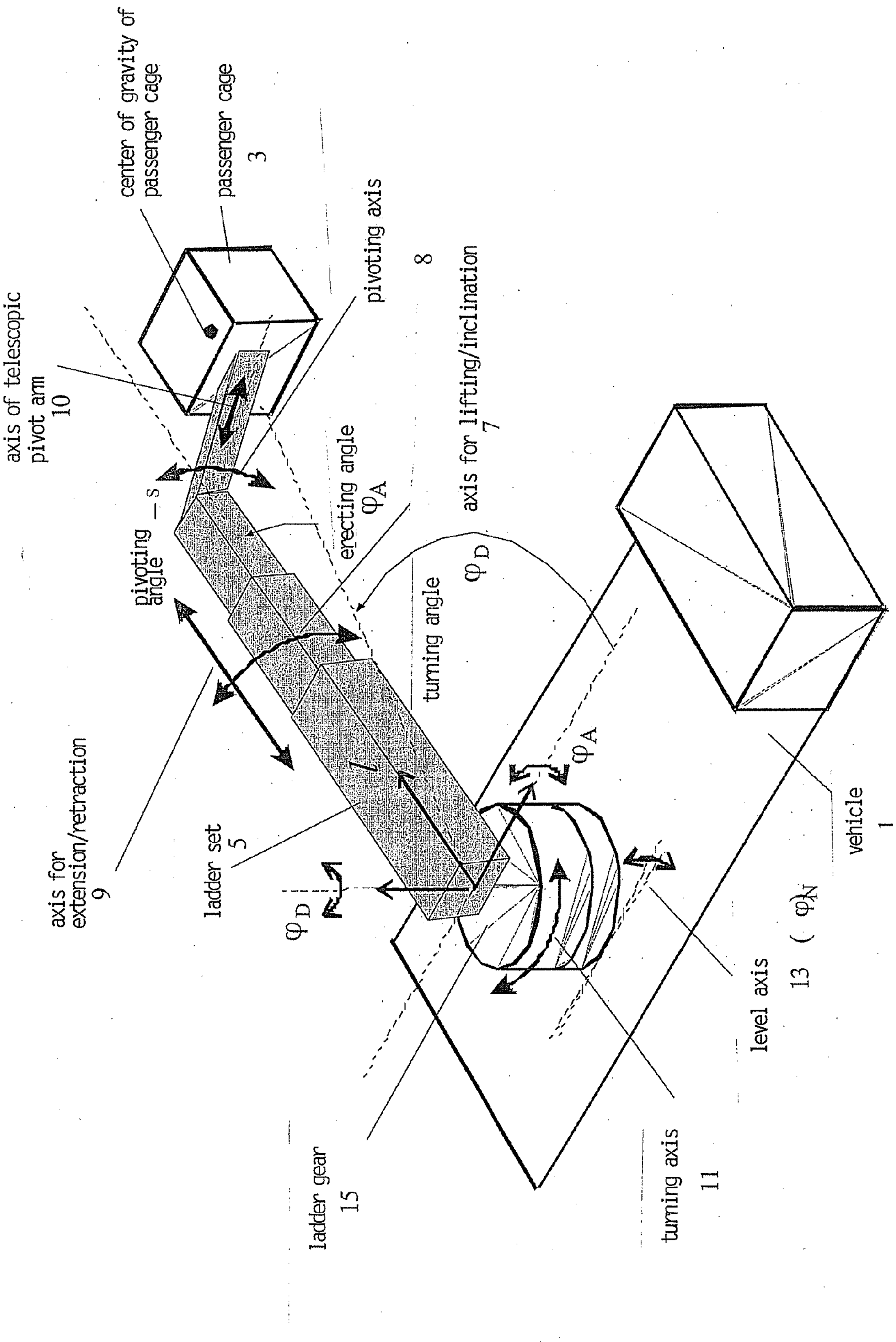

center of gravity of passenger cage
passenger cage
3
axis of telescopic pivot arm
10
pivoting axis
8
pivoting angle
s
erecting angle
φ_A
axis for lifting/inclination
7
φ_D
turning angle
axis for extension/retraction
9
ladder set
5
l
φ_D
φ_A
vehicle
1
level axis
13 (φ_N)
ladder gear
15
turning axis
11

Fig.1

Fig.2

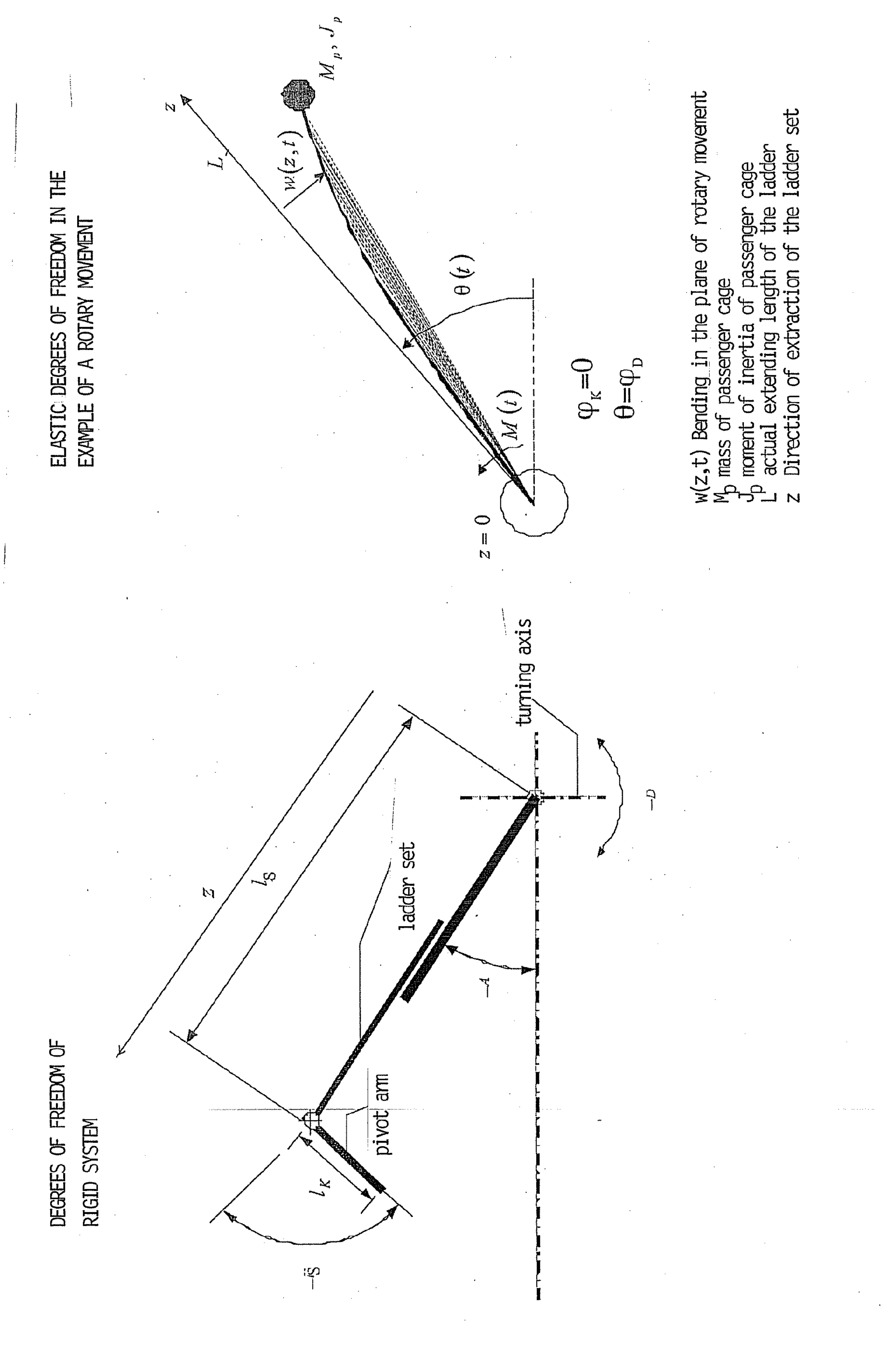

DEGREES OF FREEDOM OF
RIGID SYSTEM
pivot arm
ladder set
turning axis
z
l_S
l_K
ELASTIC DEGREES OF FREEDOM IN THE
EXAMPLE OF A ROTARY MOVEMENT
M_p, J_p
z
L
$w(z,t)$
$\theta(t)$
$M(t)$
$z = 0$
$\varphi_K = 0$
$\theta = \varphi_D$
w(z,t) Bending in the plane of rotary movement
M_p mass of passenger cage
J_p moment of inertia of passenger cage
L actual extending length of the ladder
z Direction of extraction of the ladder set

FIG. 3

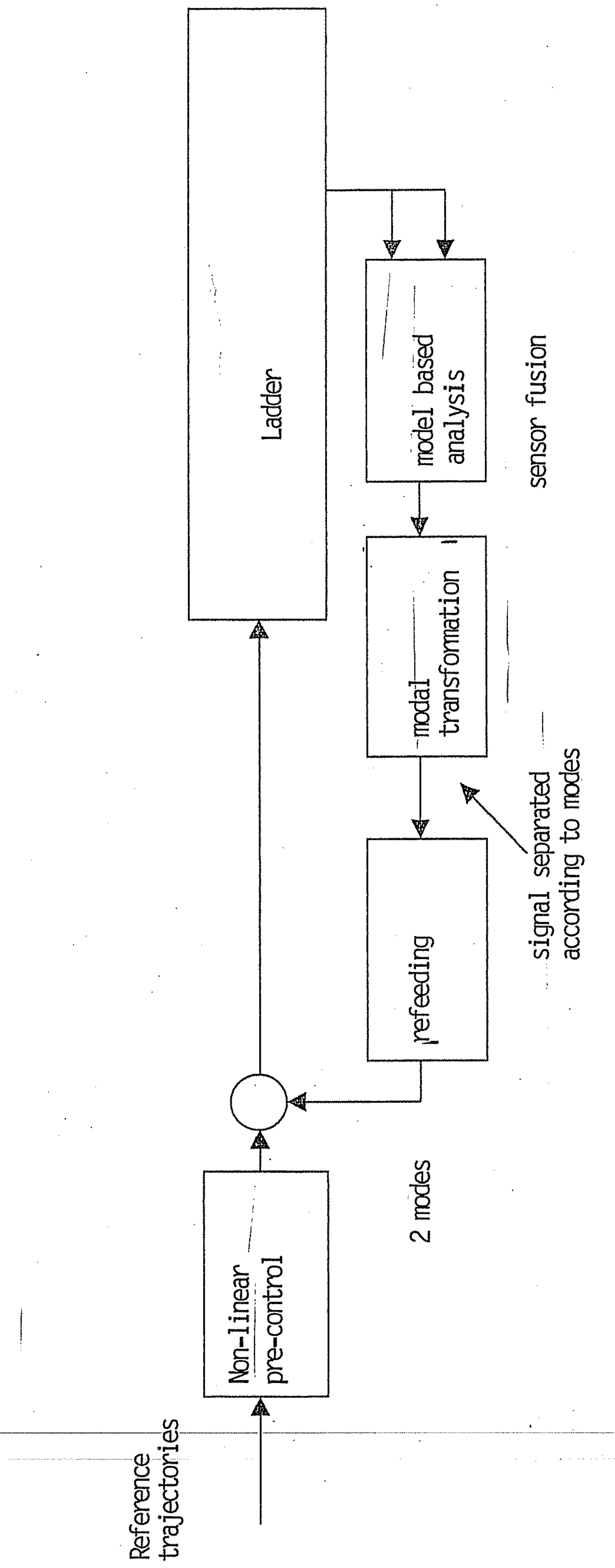

Reference trajectories
Non-linear pre-control
2 modes
refeeding
signal separated according to modes
modal transformation
model based analysis
sensor fusion
Ladder

FIG. 4

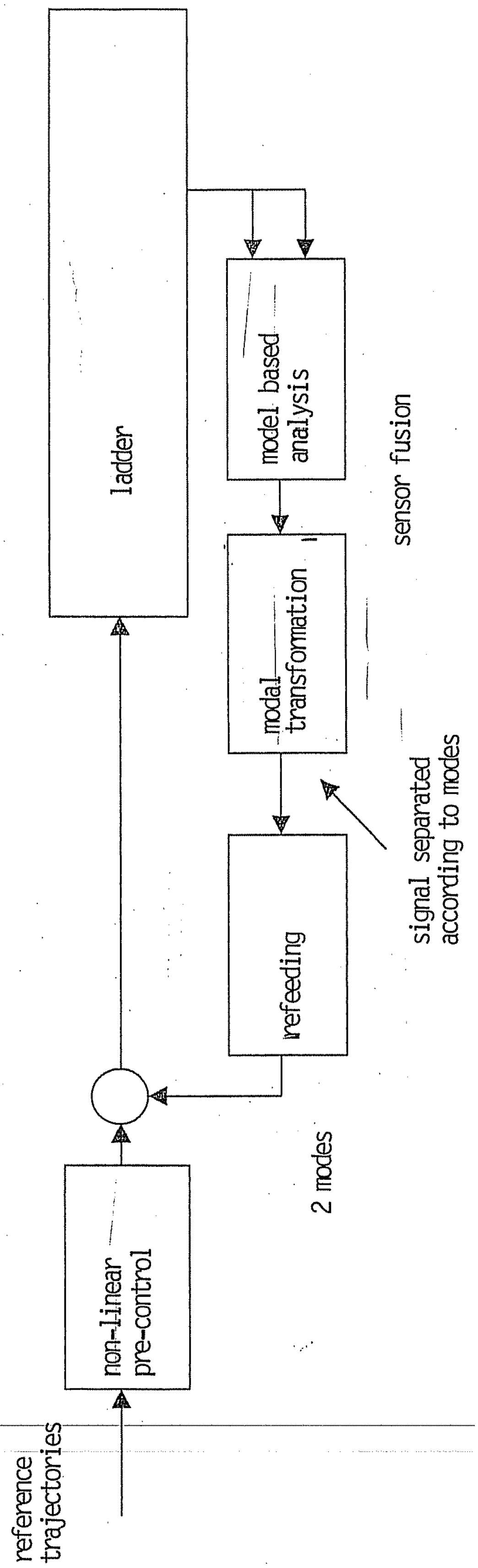

reference trajectories
non-linear pre-control
2 modes
ladder
refeeding
modal transformation
model based analysis
signal separated according to modes
sensor fusion

Fig. 5

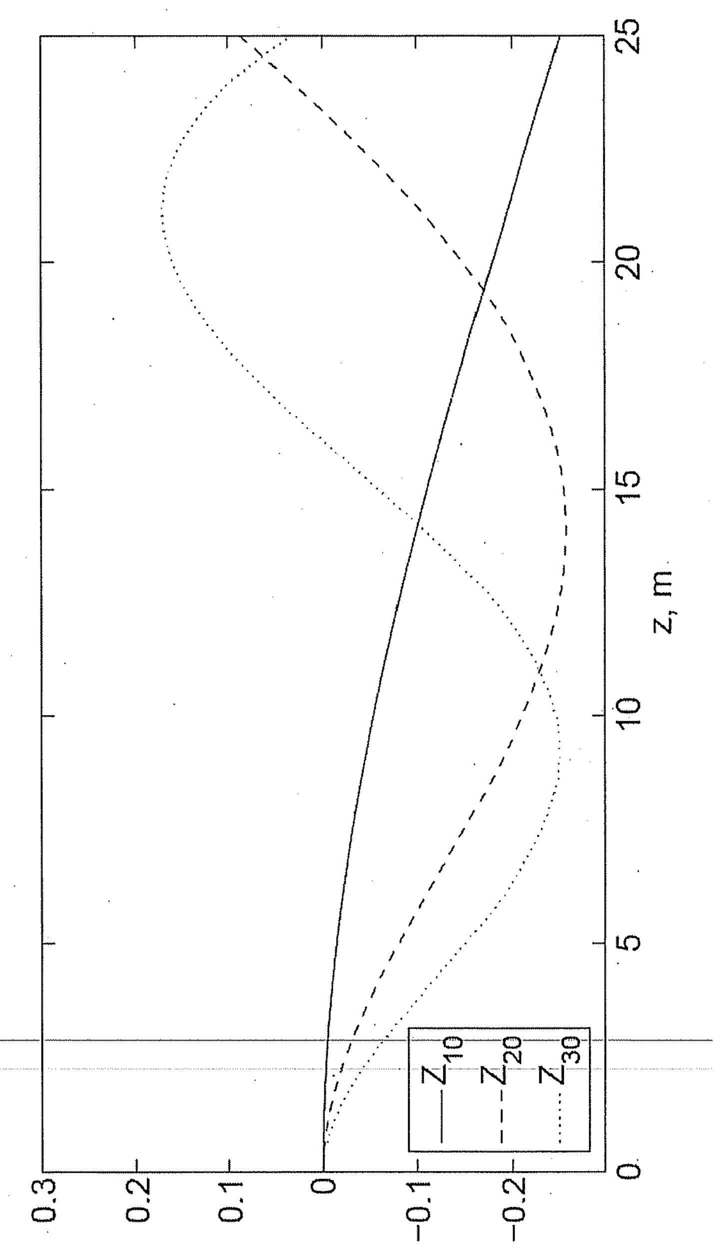


Fig. 6a

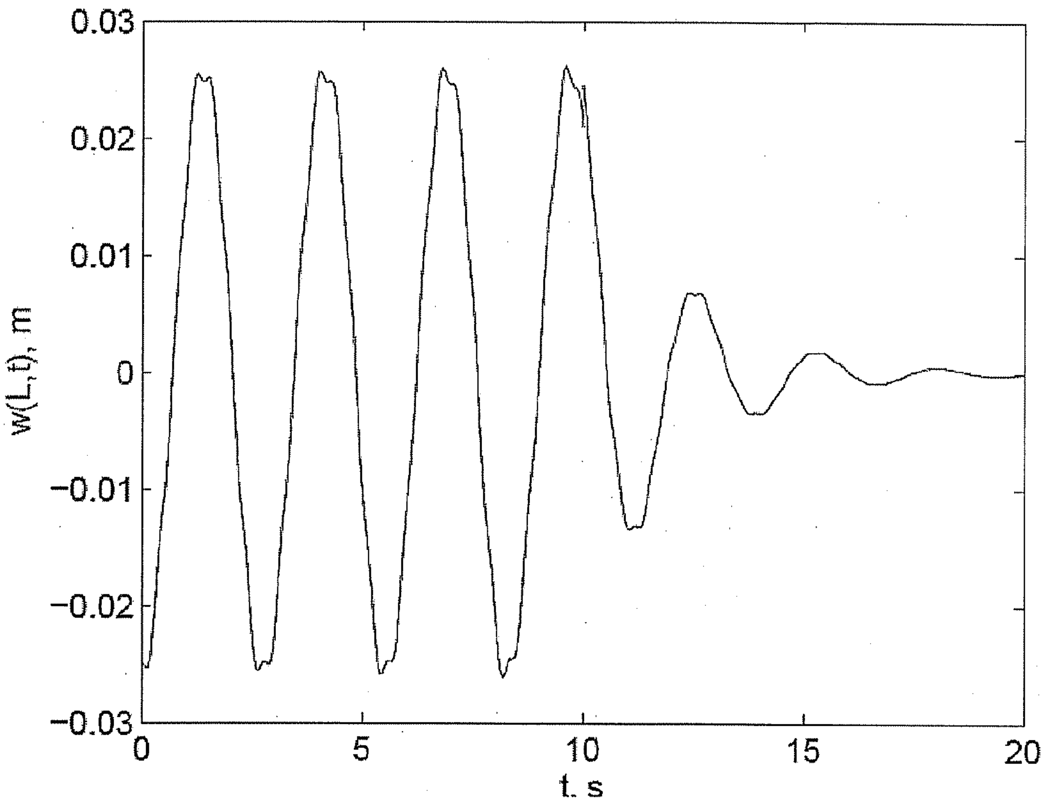
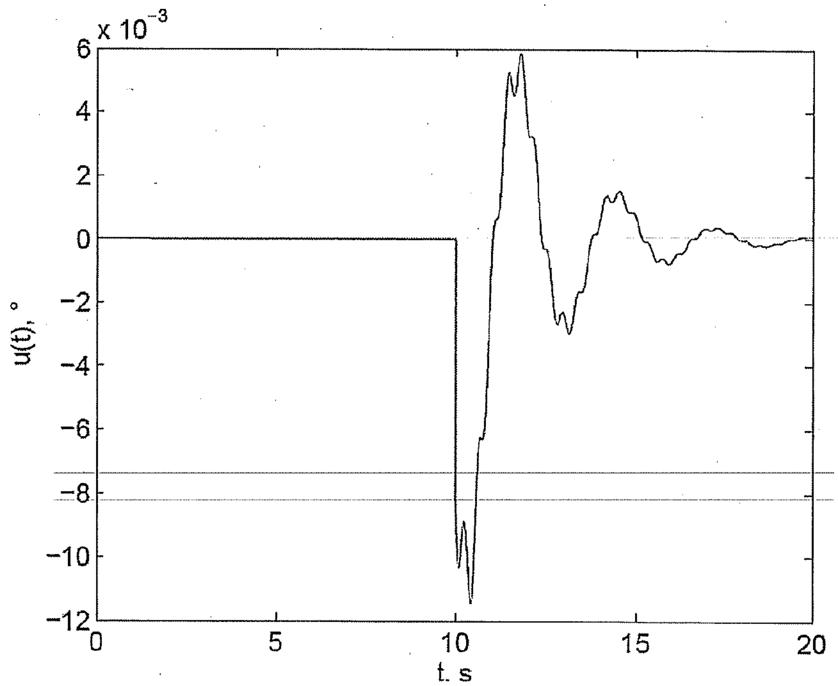

0.03
0.02
0.01
0
−0.01
−0.02
−0.03
w(L,t), m
0
5
10
15
20
t. s

Fig. 6b


x 10−3
6
4
2
0
−2
−4
−6
−8
−10
−12
u(t), °
0
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10
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20
t. s

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EUROPEAN SEARCH REPORT

Application Number
EP 08 16 2080

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The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
The Hague	13 November 2008	Sheppard, Bruce

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