Chapter 17
Non-probabilistic Uncertainty Evaluation in the Concept Phase for Airplane Landing Gear Design

Roland Platz and Benedict Götz

Abstract Predicting the kinematic and dynamic behavior of complex load bearing structures with high safety requirements such as landing gears is time consuming. For that, mathematical analytic, finite element or multi body surrogate models are needed for numeric simulation purposes. Today, these models take into account both deterministic and non-deterministic approaches. However, before adequate and verified simulation begins, the modeling of the mathematical surrogates requires most of the time for adequate prediction, including model verification, before even more costly experimental testing phase begins. This contribution investigates an approach based on INFO-GAP analysis to predict critical performance requirements of major landing gear design alternatives in an early design stage. This analysis uses only simple analytical but comparable and sufficient adequate models for four major design concept alternatives according to basic design rules found in relevant literature. The concepts comprise one telescopic and three different trailing link designs. It is the aim to make decisions in selecting the most suitable design as early as possible in the design stage with taking into account uncertainty—before time consuming efforts in modeling finite element and multi body models for detailed prediction are conducted. Particularly, the authors evaluate the robustness to uncertainty or how much of an uncertainty horizon by means of uncertain compression stroke ability due to varied stiffness properties can be tolerated with the four different concepts, until the absolute maximum allowable compression stroke limit is reached. This contribution continues the authors' prior work presented at IMAC 2016. In there, the authors evaluated and compared the performance requirements like compression stroke ability and ride quality, elastic force retention, structure strength, and weight of mechanisms for main and nose landing gears resulting from the four significant structural design concepts in mathematical physical models in an analytic deterministic way.

Keywords Landing gear • Concept evaluation • Uncertainty • INFO-GAP analysis • Decision making

17.1 Introduction

Today, numerical simulation strategies to predict the dynamic behavior comprise deterministic and statistical methods. According to [11], *all* required methods are available even in commercial codes and for sophisticated structures, geometries and materials in aerospace application. The actual challenge is caused by the high efforts of modeling set-up, management of the large amount of required input data, the management of different simulation approaches and material models over the required frequency range as far an appropriate experimental approach for model verification is concerned [11]. In the prior work [12], the authors took a first step to clarify pros and cons of different design concepts of landing gears with respect to major and typical performances requirements. It was the aim to evaluate and compare the performance requirements compression stroke ability and ride quality, elastic force retention, structure strength, and weight of mechanisms for main and nose landing gears resulting from four significant structural design concepts in mathematical physical models according to basic design rules found in [3] and [10] in an analytic deterministic way. The authors only took a first glimpse on a simple uncertainty evaluation for each concept, relating defined stiffness worst case variations in the elastic strut to the loading and compression stroke ability. The focus of the paper mainly was, though, to introduce an adequate mathematical-physical model of each concept that allows, at all, the adequate and consistent performance comparison—but without uncertainty evaluation for decision making.

R. Platz (✉)
Fraunhofer Institute for Structural Durability and System Reliability LBF, Bartningstraße 47, 64289 Darmstadt, Germany
e-mail: roland.platz@lbf.fraunhofer.de

B. Götz
System Reliability, Adaptive Structures, and Machine Acoustics SAM, Technische Universität Darmstadt, Magdalenenstraße 4, 64289 Darmstadt, Germany

R. Barthorpe et al. (eds.), *Model Validation and Uncertainty Quantification, Volume 3*,
Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-54858-6_17

Energy absorption and compliance properties are major features when evaluating the performance of landing gears in aerospace application. From the beginning of the twentieth century, airplane landing gears experience major enhancements with the invention of the telescopic oleo-pneumatic shock absorber for non retractable landing gears [1]. Different designs for non-retractable and retractable landing gears have been improved for optimal shock absorbing potential as well as enhancing strength and light-weight design for high quality and the fulfillment of allowances in aerospace industry [8]. Today, simple non retractable leaf-spring steel or composite designs for small airplanes and retractable oleo struts with and without trailing links for main and nose landing gear for small and large aircraft lead to a great variety of design concepts. Relevant specifications for landing gear design are sufficient absorption of kinetic energy and overall compliance to prevent damaging impact as well as adequate steering, stability and ride quality on the ground, high reliability, low cost, overall aircraft integration, airfield compatibility, compact design for storage, low weight etc., [4–6].

Until today, optimal damping properties of the oleo strut and optimal structural reliability and fatigue life as well as new ways of conceptional design are aspired and documented in several contributions from an academic point of view, e.g. [13–16]. However, only a few contributions discuss the pros and cons of principal landing gear concepts and give useful recommendations for the engineer who he has to decide between the concepts and oppose their requirements and benefits. For that, the engineer has to make early choices in geometry, kinematics and dynamics, e.g. whether the landing gear should have a trailing link or not. If a trailing link is in favor, further decisions have to be made concerning the position and stroke capability of the oleo strut. Yet, the position and compression stroke ability of the oleo strut affects the strength of the surrounding and supporting struts. For example, ride quality on uneven ground may be one of many criteria. The trailing link landing gear offers good ride quality since the kinematics allow larger deflection of the overall mechanism [7]. However, the cost is higher weight.

In [12], the authors proposed an approach to discuss the pros and cons for the four major landing gear design concepts

(a) telescopic design with fixed elastic strut and hinged upper/lower struts as torque links
(b) trailing link with fixed elastic strut and hinged upper/lower struts
(c) trailing link with hinged elastic strut, fixed upper strut, hinged lower strut, and high leverage
(d) trailing link with hinged elastic strut, fixed upper strut, hinged lower strut, and small leverage

in early design stage and, eventually, evaluated and compared the concepts to each other with respect to stroke ability and ride quality, elastic force retention, structure strength and total weight.

For the sake of decision making in early design stage, the authors assumed that properties from the detailed design do not alter the structural conceptional general performance [12]. In order to compare the four major landing gear design concepts (a) to (d), simplified mathematical models were introduced in [12] to ensure comparability as far as possible—knowing that usually detailed design approaches according to the guidelines in [3, 10] differ a lot and are unique for every airplane. Yet, it was the goal of that paper to prepare applicable and adequate deterministic models for early evaluation of uncertainty that comes along with different design concepts, *before* the designer gets lost in time consuming design details and *before* it might be too late to conduct major changes in the design. The mathematical models stayed simple, they all include a wheel, supporting struts and an elastic strut for elastic force retention, but arranged differently in common approaches that are included in the four major design concepts (a) to (d). However, wheel stiffness is neglected in this study.

Now, since simple but adequate deterministic mathematical modeling of the four concepts was completed in [12], in this present contribution, the four design concepts' uncertainty is evaluated using INFO-GAP analysis as a non-deterministic and non-probabilistic tool [2]. Particularly, the authors evaluate how much of an uncertainty horizon by means of uncertain absolute compression stroke ability due to varying stiffness properties can be tolerated with the four different concepts, until the absolute maximum allowable compression stroke limit is reached? How robust are the concepts against uncertainty? The tolerable uncertainty horizon is related to the total mass needed for each concept and the expected comfort or, respectively, ride quality for the different design approaches. This way, specific tolerated uncertainty will be evaluated to help decision making in selecting the most adequate design approach for landing gears in an early design stage.

17.2 INFO-GAP Theory

BEN-HAIM proposed the INFO-GAP theory that helps to quantify robustness of mathematical models based decisions despite lack of knowledge in the models [2]. Estimating the uncertainty horizon by means of uncertain absolute compression stroke ability due to varying stiffness properties for landing gear design in this present contribution takes four basic steps to apply INFO-GAP theory as shown in several other works, for example in [9] with respect to [2]. The four steps are extended by the authors for the present contribution by a specific robustness to uncertainty:

- derivation of an mathematical model $\mathcal{M}(\beta)$ with the vector β that comprises (i) model parameters such as material and geometry assumptions as well as properties like damping and stiffnesses, and (ii) state variables such as displacements, velocities, accelerations, forces and moments assumptions
- derivation of an uncertainty model

$$\mathcal{U}(\beta_0, h) = \left\{ \beta \ : \ \frac{|\beta - \beta_0|}{\beta_0} \leq h \right\}, \quad h \geq 0 \tag{17.1}$$

  taking into account assumed uncertainty in the vectors β around the vector's nominal entities β_0. The variation of β is limited by the uncertainty horizon h. A simple uncertainty model could be an interval $|\beta - \beta_0|$ related the nominal value β_0
- performance requirement

$$\mathcal{P}\Big(\mathcal{M}(\beta)\Big) \leq \mathcal{P}_{\mathrm{crit}} \tag{17.2}$$

  to specify a critical level such as limit loads etc.
- robustness to uncertainty

$$\widehat{h} = \max\{h \ : \ \max \mathcal{P}\Big(\mathcal{M}(\beta)\Big) \leq \mathcal{P}_{\mathrm{crit}}\} \tag{17.3}$$

  with the highest tolerable uncertainty horizon $\widehat{h}$.

17.3 Uncertainty Quantification in Landing Gear Design Concepts via INFO-GAP Approach

17.3.1 Guideline

For each landing gear design concept (a) to (d), the authors derive a mathematical model

$$\mathcal{M}(\beta) = z_{\mathrm{a}}(p_x, v_x) \tag{17.4}$$

to calculate the absolute compression stroke progress $z_{\mathrm{a}}(p_x, v_x)$ as a function of model parameters p_x such as density of material, geometric dimensions and other properties like stiffness k as well as state variables v_x such as static absolute loading F_{a} assumed to act on all models of the four landing gear design concepts (a) to (d). All model parameters and state variables are listed in [12]. Table 17.1 lists only a selection of model parameters and state variables that are relevant for the uncertainty evaluation in this present contribution.

Next, the uncertainty model

$$\mathcal{U}(k_0, h) = \left\{ k \ : \ \frac{|k - k_0|}{k_0} \leq h \right\}, \quad h \geq 0 \tag{17.5}$$

comprises only one varied model parameter in β: the stiffness k of the suspension rod, Sect. 17.3.2.

The performance requirement for the landing gear design,

$$\mathcal{P}\Big(z_{\mathrm{a}}\big(p_x(k), v_x\big)\Big) \leq \mathcal{P}_{\mathrm{crit}} = z_{\mathrm{a,\,max}} \tag{17.6}$$

specifies the critical or maximum allowable absolute compression stroke $z_{\mathrm{a,\,max}}$ as a result of increasing static loading F_{a}. For $z_{\mathrm{a}}\big(p_x(k), v_x\big)$ in (17.6), only the stiffness k out of all model parameters and state variables listed in [12] is assumed to be uncertain and is varied according to (17.5). Of course, all other model parameters and state variables may vary too. To the authors' opinion, however, relative to varied stiffness of the suspension strut, the variation of material and geometric parameters can be neglected due to today's high precision and accuracy in manufacturing and assembling. Stiffness variations are considered to be more likely to occur due to influence of temperature, fatigue etc.

Eventually, the robustness to uncertainty

$$\widehat{h} = \max\left\{h \;:\; \max\Big(\big|z_{\mathrm{a}}\big(p_x(k), v_x\big) - z_{\mathrm{a,\,max}}\big|\Big) \le 0\right\} \tag{17.7}$$

discloses the maximum uncertainty horizon $\widehat{h}$ for reaching the maximum allowable absolute static compression stroke $z_{\mathrm{a,\,max}}$ at static loading $z_{\mathrm{a}}\big(p_x(k), v_x\big)$ that will be tolerated for each design concept (a) to (d) when the elastic strut compliance or, respectively, stiffness k is uncertain according to (17.5).

17.3.2 Mathematical Modeling and Achieving Comparability Between the Concepts

Figure 17.1 shows real examples of the general four concepts (a) to (d) for main and nose landing gear as introduced in [12]. Their differences are based on different mounting conditions of the landing gear elements such as elastic strut and the supporting upper and lower struts or, respectively, torque links. These conditions lead to different landing gear mechanisms with their characteristic kinematics and resulting dynamics.

The concepts were simplified in [12] as schematic diagrams in Fig. 17.2 with the basic landing gear elements: elastic strut cylinder 1, elastic strut piston rod 2, upper supporting strut 3, lower supporting strut 4 or, respectively, upper torque link strut 3 and lower torque link strut 4 in (a), and wheel 5. The elastic strut's piston rod is directly connected with the wheel 5 in concept (a) or to the lower supporting strut 4 in (b) to (d). For comparative reasons, the four concepts have the same absolute installation length l_{a}, same vertical nominal static and maximum stroke ability $z_{\mathrm{a,\,stat}}$ and $z_{\mathrm{a,\,max}}$ of the wheel, and same nominal vertical static absolute load $F_{\mathrm{a,\,stat}}$ that represents the airplane's weight. In addition, the distance $x_{\mathrm{c,\,us}}$ between the elastic and upper struts support, the height h_{hinge} of the upper strut's hinge of upper strut for (b) to (d), and the distance d_{hinge} between the piston rod low end and the hinge of upper/lower strut are given for this study.

In addition to [12], the authors now investigate the uncertainty for the relation between the absolute static load F_{a} that leads to the resulting compression stroke $z_{\mathrm{a,\,stat}} \le z_{\mathrm{a}} \le z_{\mathrm{a,\,max}}$ due to uncertain stiffness k. As a performance design specification and constraint, the maximum compression stroke $z_{\mathrm{a,\,max}}$ can not be exceeded. The central question is: How much uncertainty of compliance variation or stiffness decrease for each concepts can be tolerated in order to fulfill the major requirement of not exceeding the maximum compression stroke due to static loads that are close to the static limit loads?

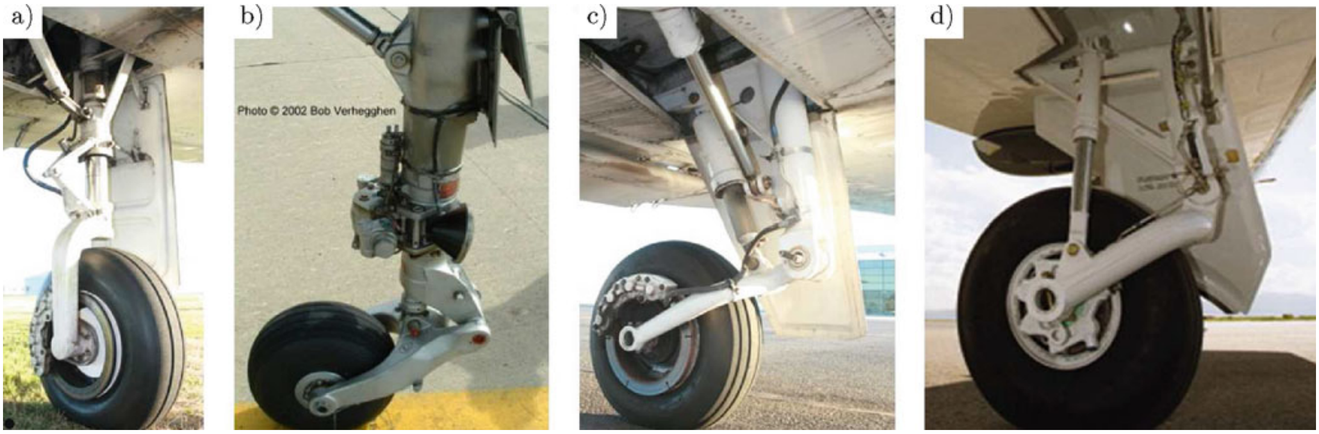

Fig. 17.1 Examples of general concepts for main and nose landing gear, (**a**) telescopic with fixed elastic strut and hinged upper/lower struts as torque links (from WIKIPEDIA), (**b**) trailing link with fixed elastic strut and hinged upper/lower struts, (from BOB VERHEGGHEN), (**c**) trailing link with hinged elastic strut, fixed upper strut, hinged lower strut, and high leverage (from WIKIPEDIA), (**d**) trailing link with hinged elastic strut, fixed upper strut, hinged lower strut, and small leverage (from PILATUS BUSINESS AIRCRAFT) [12]

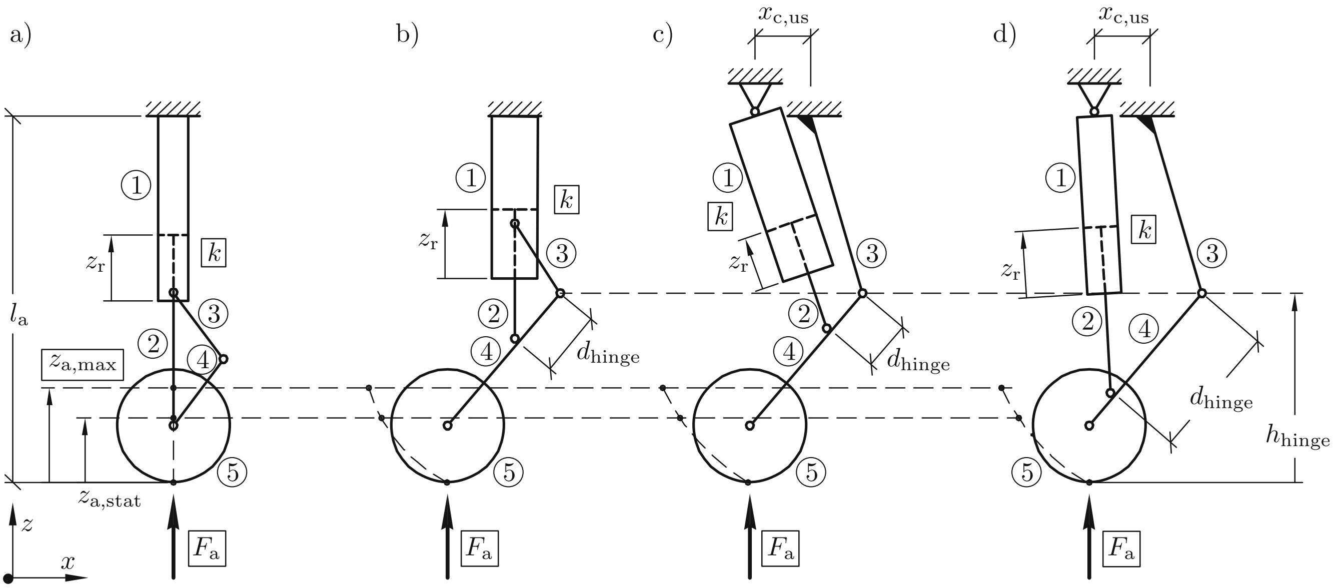

Fig. 17.2 Simplified general concepts according to [12] for main and nose landing gear with: (**a**) telescopic with fixed elastic strut (cylinder 1 and piston rod 2), hinged upper/lower struts 3/4 as torque links and wheel 5, (**b**) trailing link with fixed elastic strut (cylinder 1 and piston rod 2), hinged upper/lower struts 3/4 and wheel 5, (**c**) trailing link with hinged elastic strut (cylinder 1 and piston rod 2), fixed upper strut 3, hinged lower strut 4 with high leverage, and wheel 5, (**d**) trailing link with hinged elastic strut (cylinder 1 and piston rod 2), fixed upper strut 3, hinged lower strut 4 with small leverage, and wheel 5, [12]

17.3.2.1 Achieving Comparability Between the Concepts

Achieving comparability between different design concepts with simple models is only possible if simplifications do not oversimplify and, therefore, falsify the landing gear conceptual characteristics. The prior assumptions to achieve comparability between the concepts (a) to (d) with respect to materials, dynamics and geometry in are listed completely in [12]. Out of them, most relevant for this contribution's uncertainty evaluation are, according to Fig. 17.2:

- equal nominal static absolute axial or, respectively, nominal vertical load $F_{a,\,stat}$, referring to basic design guidelines in [3]
- equal total absolute installation length l_a as the distance between bottom wheel and elastic strut mount
- equal maximum allowable absolute vertical compression stroke ability $z_{a,\,max}$ of the mechanisms
- equal static absolute axial or, respectively, vertical nominal compression stroke $z_{a,\,stat}$ due to static airplane weight of the mechanisms

17.3.2.2 Selected Properties for Comparing the Concepts' Compression Stroke Capability Under Uncertainty

In [12], a complete list of material, dynamic and geometric properties for modeling the simplified concepts (a) to (d) was given. Table 17.1 shows a selection of the properties for comparing the concepts' compression stroke capability under uncertainty using the INFO-GAP approach. Relevant prior assumptions are listed in the first half, calculated relevant properties are listed in the second half in Table 17.1 due to the prior assumptions, including the resulting weight of the overall mechanisms. Of course, for implementation in a real airplane, further detailed design work will and must follow according to the guidelines such as in [3] and [10] to meet the manufacturer's and the regulating authorities' requirements.

The assumed linear elastic strut's stiffness nominal value becomes

$$k_0 = \frac{F_r}{z_r} \tag{17.8}$$

for each concept model (a) to (d) due to relative elastic strut loads F_r and strokes z_r, with the identity to absolute loads and strokes $F_r = F_a$ and $z_r = z_a$ in (a). The relation in (17.8) has been derived by adapting the relative load and stroke relation to the overall requirement of equal nominal static absolute vertical load $F_{a,\,stat}$ and equal nominal static absolute vertical stroke $z_{a,\,stat}$ that are assumed for all four concepts and listed in Table 17.1 and according to [12]. The rather complex modeling of the kinematic relations has been done numerically with finite element calculation and is not shown here.

Table 17.1 Dynamic, geometric and material properties as well as resulting weight for the simplified concepts (a) to (d) according to Figs. 17.1 and 17.2 to ensure comparability, density steel: $\rho = 7.850\,\mathrm{kg/m^3}$, material for all elements: D6AC 4335V, mass of wheel: neglected, n.s. = not specified [12]

Property	Variable	Unit	(a)	(b)	(c)	(d)
Prior assumptions to achieve comparability						
Load, nominal static absolute	$F_{\mathrm{a,\,stat}}$	kN	30.0	30.0	30.0	30.0
Height hinge of upper strut (b) to (d)	h_{hinge}	m	n.s.	0.450	0.450	0.450
Distance between mounting of cylinder and upper strut	$x_{\mathrm{c,\,us}}$	m	–	–	0.125	0.125
Distance piston rod low end to hinge upper/lower strut	d_{hinge}	m	n.s.	0.158	0.118	0.315
Compression stroke, maximum vertical static absolute wheel	$z_{\mathrm{a,\,max}}$	m	0.250	0.250	0.250	0.250
Compression stroke, nominal vertical static absolute wheel	$z_{\mathrm{a,\,stat}}$	m	0.170	0.170	0.170	0.170
Calculated properties due to prior assumptions						
Stiffness, elastic strut	k_0	kN/m	120.0	660.0	1260.0	241.2
Load, maximum absolute	$F_{\mathrm{a,\,max}}$	kN	44.118	40.410	37.328	42.000
Load, maximum relative elastic strut	$F_{\mathrm{r,\,max}}$	kN	44.118	85.085	119.289	52.095
Load, static relative elastic strut	$F_{\mathrm{r,\,stat}}$	kN	30.000	59.097	85.791	36.297
Stroke, maximum relative elastic strut	$z_{\mathrm{r,\,max}}$	m	0.250	0.129	0.095	0.216
Stroke, static relative elastic strut	$z_{\mathrm{r,\,stat}}$	m	0.170	0.090	0.068	0.150
Mass, total system	m	kg	19.82	32.96	53.00	29.49

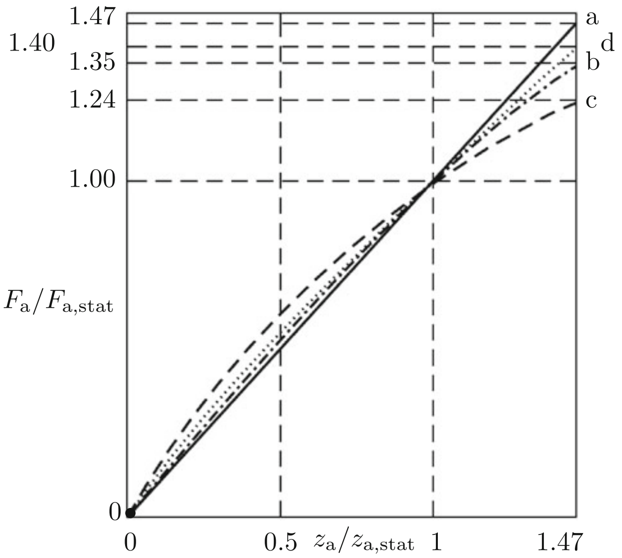

Fig. 17.3 Static load F_{a} vs. static compression stroke z_{a}, normalized to the nominal static absolute load $F_{\mathrm{a,\,stat}}$ and to the nominal vertical static absolute stroke $z_{\mathrm{a,\,stat}}$ for concept (a) *black solid line*, (b) *black dot-dashed line*, (c) *black dashed line*, and (d) *black dotted line*

17.3.2.3 Deterministic Comparison of Static Compression Stroke Behavior

In this section and at first, the authors repeat to evaluate and compare the distinctive compression stroke ability $z_{\mathrm{a}}(p_x, v_x)$ without varied stiffness k due to static loading F_{a} resulting from significant structural design concepts (a) to (d) from [12].

Figure 17.3 shows the progress of load vs. stroke relations F_{a} vs. z_{a} for the absolute vertical wheel stroke z_{a} for concepts (a) to (d), Fig. 17.2 [12]. The relations are normalized to the nominal static absolute load $F_{\mathrm{a,\,stat}}$ and nominal vertical static absolute stroke $z_{\mathrm{a,\,stat}}$. Uncertainty is not taken into account, the relations are derived from deterministic calculation. In case of the absolute load-stroke relation F_{a} vs. z_{a} of the overall mechanism, the relation in concept (c) is most nonlinear due to the high leverage effect. Concept (c) ensures smoothest ride quality of all, concept (a) leads to rather bumpy rides. In case the absolute stroke exceeds the absolute static stroke by the factor of 1.47 due to higher loading than the static load, the maximum allowable stroke is reached. Concept (a) allows highest absolute loading than concept (c) with lowest absolute loading capability.

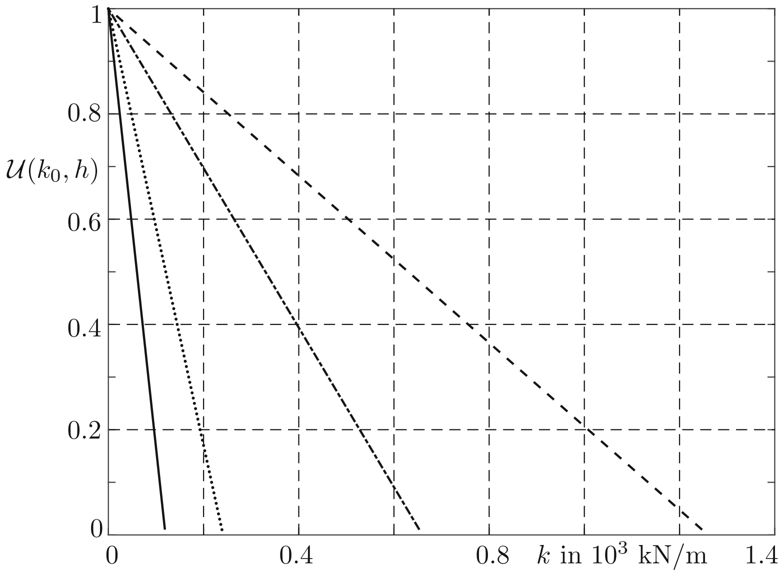

Fig. 17.4 Uncertainty for varied decreasing stiffnesses k when deviating from the nominal values k_0 according to Table 17.1 for each concept (a) *black solid line*, (b) *black dot-dashed line*, (c) *black dashed line*, and (d) *black dotted line*

17.3.3 Uncertainty Model

Each concept (a) to (d) leads to an uncertainty model (17.5) with different varied stiffnesses k according to different nominal stiffness values k_0 listed in Table 17.1. Figure 17.4 shows the progress of decreasing stiffness k for the concepts. For $\mathcal{U}(k_0, h) = 0$, the stiffnesses $k = k_0$ for concepts (a) to (d). For $\mathcal{U}(k_0, h) = 1$, all stiffnesses would be zero, that would be a total failure of the suspension rod and unlikely to happen.

From an engineering point of view, only the uncertainty in decreasing stiffness is of interest, since decreasing stiffness means a higher relative compression stroke z_r for a given constant relative loading F_r, see (17.8) and Fig. 17.2. Higher relative static compression stroke, in turn, means lowering the safety margins in reaching the maximum absolute static compression $z_{\mathrm{a,\,max}}$

17.3.4 Performance Requirement

The effectual performance requirement (17.6) has been thoroughly explained in the guideline Sect. 17.3.1. The critical or maximum allowable absolute compression stroke $z_{\mathrm{a,\,max}}$ should not be reached.

17.3.5 Robustness to Uncertainty

Figure 17.5 shows the robustness or maximum uncertainty horizon $\widehat{h}$ as expelled maximum values of h according to (17.7) for varied stiffnesses k when the maximum allowable static absolute compression stroke $z_{\mathrm{a,\,max}} = 1.47 \cdot z_{\mathrm{a,\,stat}}$, Table 17.1, is reached for all landing gear design concepts (a) to (d) and for different absolute static loads F_a in four cases (A) to (D).

For case (A), a constant static absolute load $F_\mathrm{a} = 1 \cdot F_{\mathrm{a,\,stat}}$ is assumed. For all design concepts (a) to (d), robustness $\widehat{h}$ is greater than 0.19. That means that for the nominal static load $F_{\mathrm{a,\,stat}}$, a safety margin for at least 19% robustness is given for varied stiffnesses for all concepts. The highest robustness 32% is given for concept (a), the lowest with 19% for concept (c).

For case (B), a constant static absolute load $F_\mathrm{a} = 1.10 \cdot F_{\mathrm{a,\,stat}}$ is assumed. For all design concepts (a) to (d), robustness $\widehat{h}$ is greater than 0.11. That means that for the static load $1.10 \cdot F_{\mathrm{a,\,stat}}$, a safety margin for at least 11% robustness is given for varied stiffnesses for all concepts. The highest robustness 25% is given for concept (a), the lowest with 11% for concept (c).

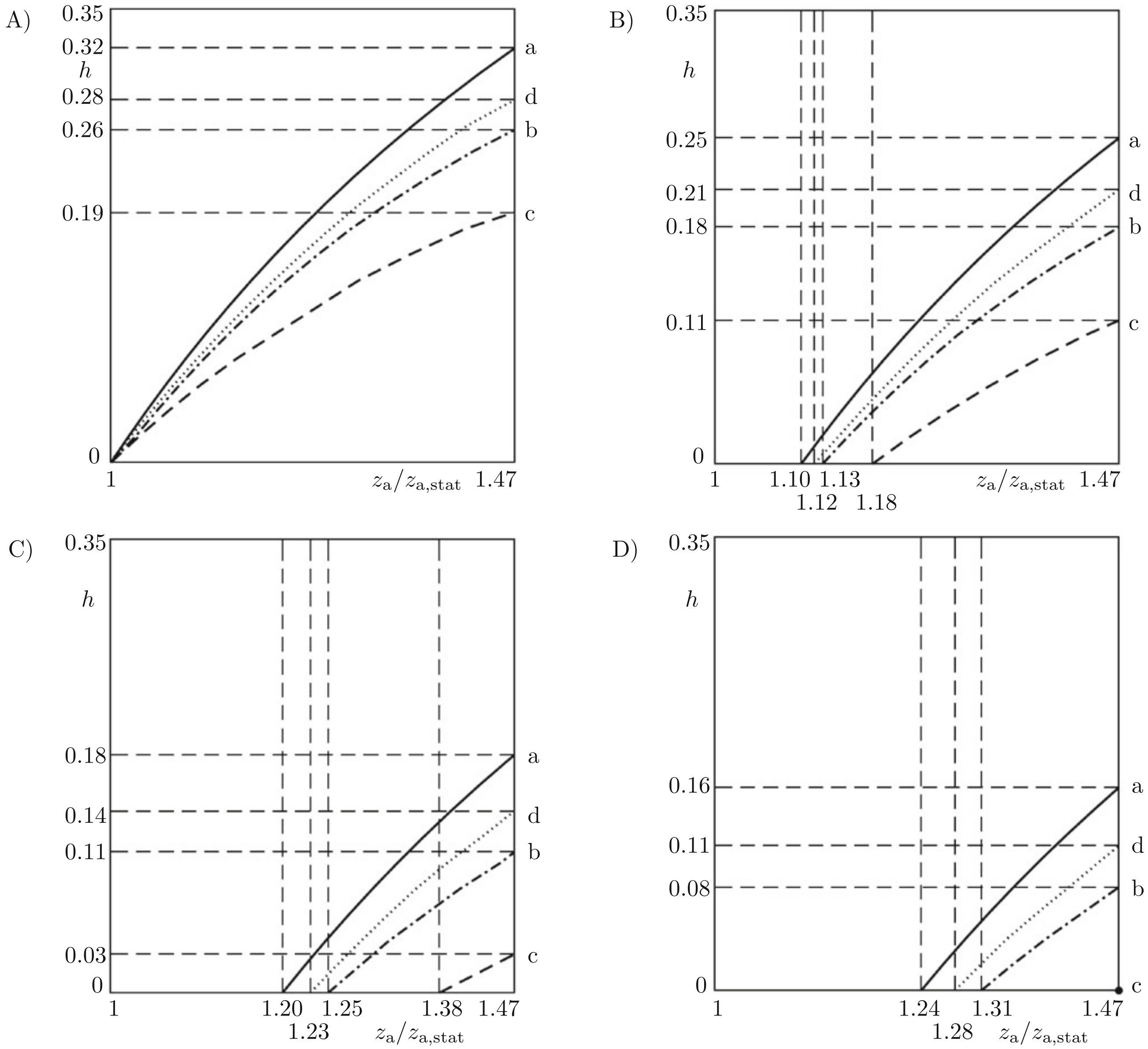

Fig. 17.5 Uncertainty horizon h as a result of varied decreasing stiffness k according to (17.5) vs. the compression stroke z_a, normalized to the nominal static absolute stroke $z_{a,\,stat}$ for (**A**) static load $F_a = 1 \cdot F_{a,\,stat}$, (**B**) $F_a = 1.10 \cdot F_{a,\,stat}$, (**C**) $F_a = 1.20 \cdot F_{a,\,stat}$, and (**D**) $F_a = 1.24 \cdot F_{a,\,stat}$ with respect to the landing gear concepts (a) *black solid line*, (b) *black dot-dashed line*, (c) *black dashed line*, and (d) *black dotted line*

For case (C), a constant static absolute load $F_a = 1.20 \cdot F_{a,\,stat}$ is assumed. For all design concepts (a) to (d), robustness $\widehat{h}$ is greater than 0.03. That means that for the static load $1.20 \cdot F_{a,\,stat}$, a safety margin for at least 3% robustness is given for varied stiffnesses for all concepts. The highest robustness 18% is given for concept (a), the lowest with 3% for concept (c).

For case (D), a constant static absolute load $F_a = 1.24 \cdot F_{a,\,stat}$ is assumed. Only for the design concepts (a), (b) and (d), robustness $\widehat{h}$ is greater than 0.08. That means that for the static load $1.24 \cdot F_{a,\,stat}$, a safety margin for at least 8% robustness is given for varied stiffnesses for these concepts. The highest robustness 16% is given for concept (a), no robustness with 0% for concept (c).

17.4 Conclusion

This contribution verifies the usefulness of the INFO-GAP approach to quantify uncertainty for major landing gear design concepts in a non-probabilistic way in early design stage. The concepts comprise one telescopic and three different trailing link designs. They are modeled mathematically in a simple but adequate analytic way according to guidelines found in distinctive literature. It is assumed that the stiffness of the integrated elastic strut is varied. The uncertainty in stiffness has major impact on the static compression stroke ability of the landing gears. The robustness to uncertainty of reaching the maximum allowable static compression stroke as a result to varied stiffness, and not as a result of exceeding maximum loading, could be quantified. The uncertainty quantification shows that the concept with the telescopic design with fixed elastic strut and hinged upper/lower struts as torque links is most robust against varied stiffness, whereas the concept with trailing link, hinged elastic strut, fixed upper strut, hinged lower strut, and high leverage is least robust. As an outlook, the authors will have a closer look to additional varied parameters to get an even more distinctive view on the uncertainty in the design concepts at early design stage.

Acknowledgements The authors like to thank the German Research Foundation DFG for funding this research within the SFB 805.

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