ISO/DPAS 5672:2023(E)

ISO/TC 299

Secretariat: SIS

Date: 2023-07-24

Robotics — Collaborative applications — Test methods for measuring forces and pressures in human-robot contacts

DPAS stage

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Contents

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This document was prepared by Technical Committee ISO/TC 299, *Robotics*.

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Introduction

All testing methods specified in this document represent the latest state-of-the-art in the research field of contact measurement and testing with robots made for biomechanically safe interactions with humans. The procedures described in this document have been developed with a focus on practical applicability and several examples have been included in the annexes to this effect. –The intended users of the document include integrators, operators, and users of collaborative applications as well as manufacturers of pressure-force measurement devices (PFMD).

The purpose of this document is to facilitate the application of other standards such as ISO 10218-2, Annex– N, robot applications and robot cells integration (based on RIA TR R15.806:2018) or ISO/TS 15066:2016.

Robotics — Collaborative applications — Test methods for measuring forces and pressures in human-robot contacts

1 Scope

This document specifies methods of measuring forces and pressures in physical human-robot contacts. It also specifies methods for analyzing the measured forces and pressures. It further specifies the characteristics of pressure-force measurement devices (PFMD).

This document applies to collaborative applications deployed in an industrial or service environment for professional use.

This document does not apply to non-professional robots (i.e. consumer robots) or medical robots, although the measurement methods presented can be applied in these areas, if deemed appropriate. Additionally, this document does not apply to organizational aspects for performing contact measurements (e.g. responsibilities or data management), assessment of other mechanical contact types (e.g. friction or shearing), assessment of other contact-related hazards (e.g. falling, electrical or chemical hazards). Further, this document does not set requirements for specific PFMD-design or specify methods to identify contact hazards.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10218-2,[1] *Robotics — Safety requirements — Part 2: Industrial robot systems, robot applications and robot cells*

ISO 12100, *Safety of machinery — General principles for design — Risk assessment and risk reduction*

ISO/IEC Guide 50, *Safety aspects — Guidelines for child safety in standards and other specifications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12100 and ISO~~/FDIS~~ 10218-2 and the following apply.

ISO and IEC maintain ~~terminological~~terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
contact hazard

[1] Under preparation. Stage at the time of publication: ISO/FDIS 10218-2:2023.

intended or unintended physical contact between human and robot or robot system in which the robot or robot system exerts forces and pressures on the human body

3.2
pressure-force measurement device
PFMD
measuring instrument with sensors to record forces and pressures of mechanical contacts

3.3
biomechanical response
behavior of a biological system when subjected to mechanical load that can be described by *biomechanical response curves* (3.4)

3.4
biomechanical response curve
curves that plot the contact force as a function of tissue deformation

4 Overview

4.1 General

The test methods presented in this document provide evidence through measurement whether a robot or robot system (hereinafter referred to as robot for simplicity) deployed in a collaborative application (hereinafter referred to as application for simplicity) complies with applicable force and pressure limits during physical contact with humans. Physical contact can result either from intended use or reasonably foreseeable misuse of the robot under test.

The testing procedure typically comprises several measurements of contact hazards (as identified by the risk assessment) that are replicated with the robot deployed in the target application environment. In such tests the forces and pressures, that the robot can exert on humans during physical contact, are measured. The robot passes the tests if the contact forces and pressures measured in the relevant contact situations do not exceed the applicable biomechanical limits.

If the applicable biomechanical limits also apply to children, the measurement procedures given in this document shall be executed in accordance ~~to~~with ISO/IEC Guide 50~~:2014~~.

A pressure-force measurement device (PFMD) is used to measure forces and pressures, but also to replicate the biomechanical response of the human body. For replicating the biomechanical response, a PFMD can comprise various viscous and elastic materials.

The following list summarizes the steps of a proper test:

a) Preparation of the robot and the test conditions

b) Replicating the contact situation by letting the robot under test collide with the PFMD

c) Analyzing the forces and pressures measured

d) Comparing the measurement values to the applicable biomechanical limits (if the measurement values do not exceed the biomechanical limits, the robot passes the test for the target application environment; otherwise, it does not pass the test)

e) Documentation of the test results

f) If the robot does not pass the test for the target application environment, it will be possible to reduce force and/or pressure by modifying the robot. Repeat all the steps from a) to e) if the robot is modified and document the new test conditions.

4.2 Contact types

Human-robot contact situations can be categorized into intended or unintended contacts. Intended human-robot contacts are typically interactions between human and robot to complete a common task. Unintended human-robot contacts typically result from reasonably foreseeable misuse. Both contact categories shall be assessed through measurement if identified as relevant by the risk assessment. From here on, both contact categories will be referred to as *contact hazard*.

Any contact hazard can be classified by the following independent key contact characteristics:

1) Load profile – describes the course of the contact force and pressure measured over time. It can be either *quasi-static* (contact force and pressure change slowly over contact time; no distinct global maximum) or *dynamic* (contact force and pressure oscillate quickly over contact time; distinct global maximum).

2) Spatial configuration – indicates the presence or absence of rigid obstacles that can restrict the ability of the human body to recoil. It can be either *constrained* (obstacle restricts body part from recoiling; body part is pinched) or *unconstrained* (no obstacle; body part can recoil).

NOTE 1 A condition for unconstrained spatial configurations is the free distance to the next fixed object or obstacle which is at least 500 mm. More precise distance values can be found in ISO 13854:2017.

All possible combinations of the key contact characteristics lead to the following contact types:

1) Push – robot moves against the moveable and spatially unconstrained body part. The force and pressure increase slowly with time while the robot continues to move (i.e., quasi-static load profile). When the body part contacted has the same speed as the robot, the force or pressure remains at a constant level.

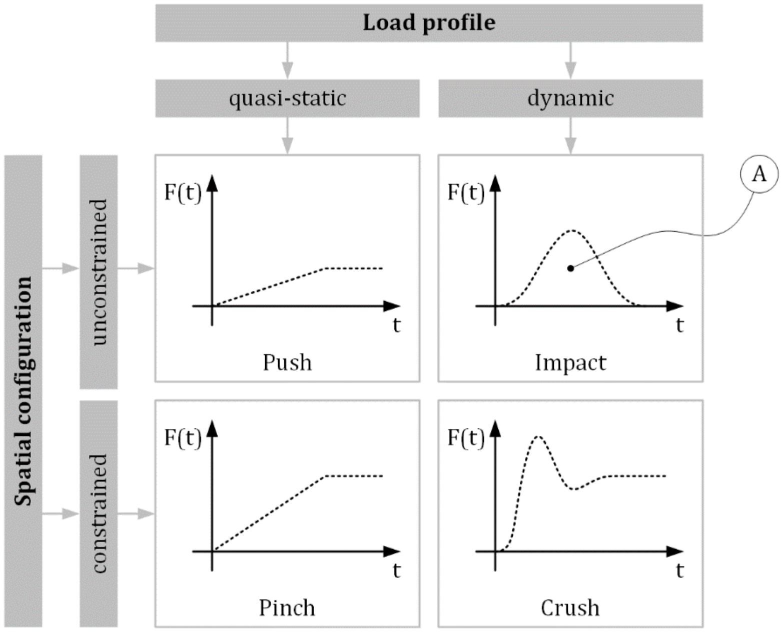
2) Pinch – robot moves against the unmovable and spatially constrained body part. The force and pressure increase slowly with time and remains at a constant level once the robot has stopped (i.e., quasi-static load profile).

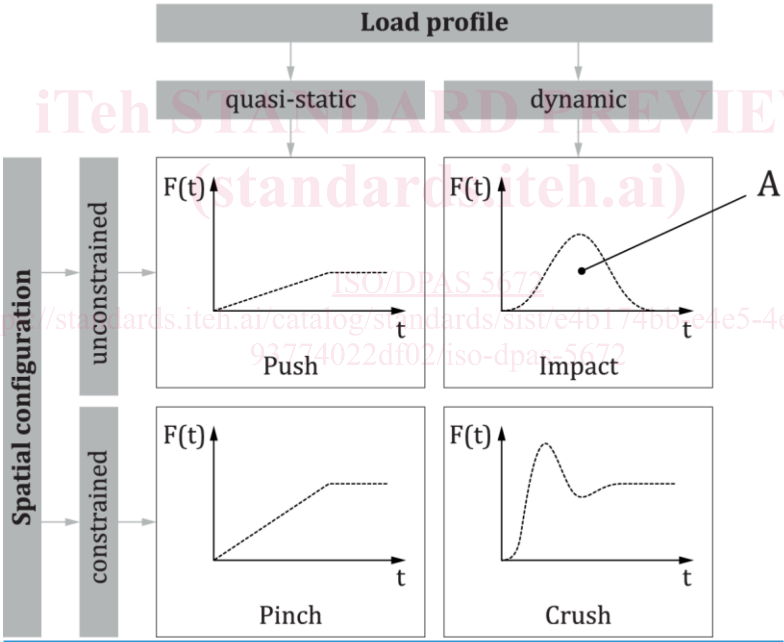
3) Impact – robot moves against the moveable and spatially unconstrained body part. The force and pressure increase quickly with time and decrease quickly to zero after reaching its maximum (i.e., dynamic load profile).

4) Crush – robot moves against the unmovable and spatially constrained body part. The force and pressure increase quickly with time (i.e., dynamic load profile) and remains at a constant value after reaching its maximum once the robot has stopped.

NOTE 2 A quasi-static load profile typically occurs when a robot moves against a body part at lower speeds (i.e., driving forces dominate). A dynamic load profile typically occurs when a robot moves against a body part at higher speeds (i.e., inertial forces dominate).

~~Figure 1~~Figure 1 assigns the expression to both key contact characteristics and illustrates typical courses of the contact force.





Key

A ~~Illustration~~illustration of the contact force plotted as a function of time

Figure ~~1~~ 1 — Key contact characteristics of contact hazards and their relation to specific contact types

The contact type *push* typically does not need to be tested unless the risk assessment specifies otherwise. The risk from such contacts is typically low since the human will be able to release the contact easily. In case the risk assessment specifies a push relevant for testing, this contact type shall be treated as a pinch. All other contact types shall be assessed through measurement unless the risk assessment specifies otherwise.

4.3 Contact locations

Contact hazards typically occur on moving parts of the robot such as:

— Links, joints, housing of the robot

— End-effector

— Workpiece handled by robot

— Other periphery (e.g., dress packs)

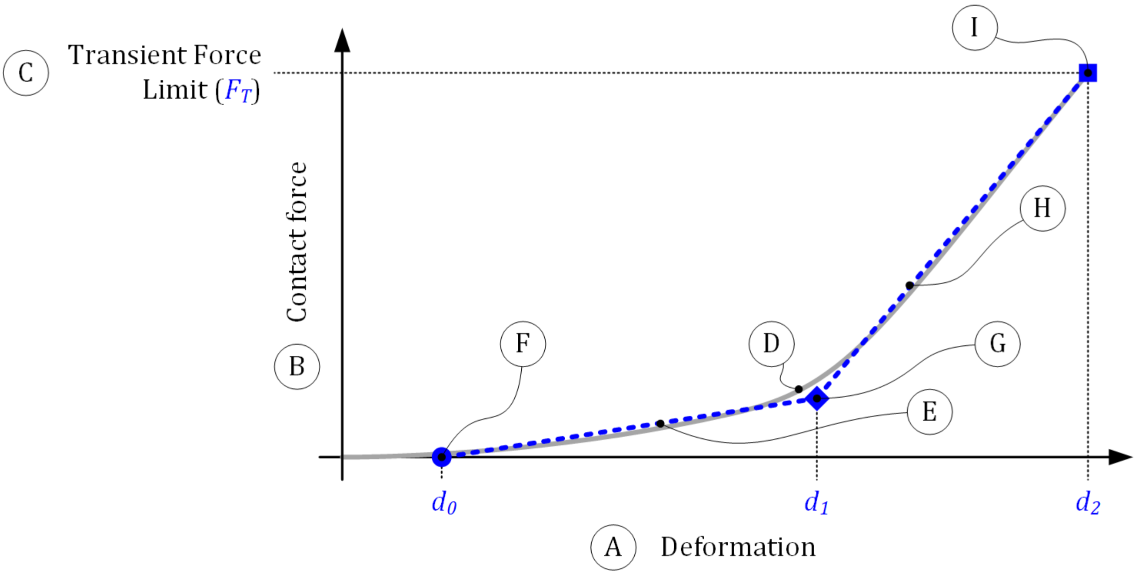
Contacts can also occur with structures in the environment of the robot. Especially before testing pinch or crush points, it should be identified if the contact surface with the smallest curvature radii is on the robot or on the obstacle in the environment of the robot. The pressure shall be measured on the outward part of the surface with the smallest curvature radii.

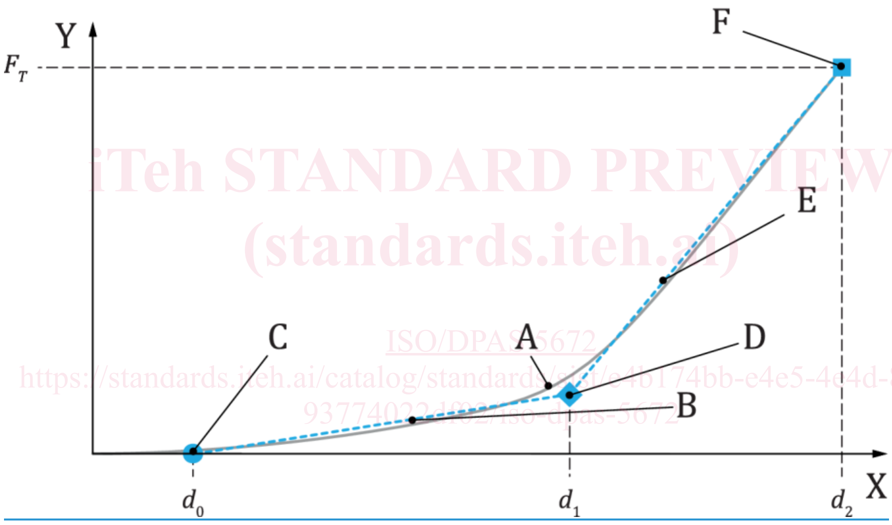
5 Measuring instrument

5.1 General

This document addresses only the mechanical response of a PFMD to contact and does not describe a specific design of a PFMD. The response of a PFMD can be expressed by a function of contact force over deformation. Like biomechanical response curves, the function describes the contact force that occurs at a specific deformation of the human body part and vice versa.

In context of a PFMD, the contact force is the force measured by a PFMD force sensor. As for human tissue, the force acting on a PFMD causes a deformation of its elastic components. A properly designed and/or configured PFMD should replicate a given biomechanical response curve within the allowable design tolerances specified in 5.2.5.2.





Key

AX Deformationdeformation of a human body part under contact force

BY Contactcontact force applied to a human body part

CF_T Forceforce limit for transient contact phase

DA Responseresponse curve as derived from the same biomechanical data that were used to determine the transient force limit

EB Firstfirst line that approximates the first part of a response curve (i.e., from d_0 d_0 to d_1) d_1)

FC Point (d_0)point (d_0) at which the first line intersects with the deformation axis

GD Point (d_1)point (d_1) at which both lines intersect

HE Secondsecond line that approximates the second part of the response curve (i.e., from d_1 d_1 to d_2) d_2)

IF Point (d_2)point (d_2) at which the second line intersects the transient force limit

Figure 2 2 — Illustration of a typical response curve for a specific human body part

~~Figure 2~~Figure 2 displays a typical biomechanical response curve. Every curve is only valid for a specific human body part and shall be developed from the same data from which the applicable transient force limit was derived. When comparing a PFMD response with the reference response from biomechanical experiments, the response curve of the PFMD shall be measured with an indenter (i.e., contact body or probe) with the same characteristics as the one that is specified by the source that provides the biomechanical response curves.

As shown in ~~Figure 2~~Figure 2 by (D), a response curve can be divided into two parts. In the first part of the response curve, the contact force increases slightly as the deformation increases until the deformation reaches a characteristic point. This part of the response typically contributes little to the overall response and the maximum contact force. After the characteristic point, the response curve becomes steeper. This steeper part of the response curve shall extend at least to the transient force limit to be applied for the body part replicated by the curve.

5.2 Design parameters

To obtain a minimum number of numerical parameters for properly designed PFMDs, a response curve shall be approximated by two lines. The first line shall approximate the first part of the response curve (from ~~d_0~~ d_0 to ~~d_1).~~ d_1). It intersects with the abscissa (deformation axis) at ~~d_0~~ d_0 with ~~$d_0 \geq 0$.~~ $d_0 \geq 0$. An intersection should not occur for negative deformation values. The first line shall end at the characteristic deformation ~~(d_1)~~(d_1) at which the response curve becomes steeper, and the second approximation line begins. Let ~~d~~ d be the deformation variable, then the first line is defined by:

~~$F_1(d) = c_1 \times (d - d_0)$ (1)~~

$$F_1(d) = c_1 \times (d - d_0) \quad (1)$$

for any deformation ~~(d)~~(d) between ~~d_0~~ d_0 and ~~d_1,~~ d_1 , i.e., ~~$d_0 \leq d \leq d_1$.~~ $d_0 \leq d \leq d_1$.

The second line shall approximate the second part of the response curve (from ~~d_1~~ d_1 to ~~d_2).~~ d_2). It begins at the point at which the first line ends per definition ~~(d_1)~~(d_1) and ends at the point ~~(d_2)~~(d_2) at which it intersects the transient force limit. Then, the second line is defined by:

~~$F_2(d) = c_2 \times (d - d_1) + F_1(d_1)$ (2)~~

$$F_2(d) = c_2 \times (d - d_1) + F_1(d_1) \quad (2)$$

for any deformation ~~(d)~~(d) between ~~d_1~~ d_1 and ~~d_2,~~ d_2 , i.e., ~~$d_1 < d \leq d_2$.~~ $d_1 < d \leq d_2$.

Both deformation intervals, defined by equation ~~(1)~~ (1) and ~~(2),~~(2), give the following parameters for a properly designed PFMD:

~~D_1 — Distance between d_0 and d_1, i.e., $D_1 = d_1 - d_0$~~
~~c_1 — Slope of the first line~~
~~c_2 — Slope of the second line~~

- D_1 — Distance between d_0 and d_1 , i.e., $D_1 = d_1 - d_0$
- c_1 — Slope of the first line

- c_2 Slope of the second line

NOTE The PFMD design parameters and the biomechanical limits belong together and thus have ideally to come from the same source.

Specific values for these parameters are only valid for a particular human body part. They should, therefore, be provided in combination with the limits for the associated human body part.

5.3 Calibration

For calibration, a PFMD response curve shall be measured using an indentation system that displaces the PFMD at a constant indentation speed of 1 mm/s until the contact force reaches the transient force limit that is given for the body part. During the calibration, force and deformation shall be measured with a sampling frequency of ~~≥ 100 Hz~~ $\geq 100\,\text{Hz}$ and at a resolution of ~~≤ 1 N~~ $\leq 1\,\text{N}$ and ~~≤ 0,1 mm.~~ $\leq 0{,}1\,\text{mm}$. Signal filters shall not be applied. The contact body that transfers the force from the indentation system to the PFMD shall be the same as the one indicated by the source of the reference response curves or curve parameters.

Once the response curve is measured accordingly, it shall be approximated by two lines. The first line shall approximate the first of the response curve (from ~~d_0~~ d_0 to ~~d_1)~~ d_1) and the second line the second part (from ~~d_1~~ d_1 to ~~d_2).~~ d_2). For the approximation of the first part, the starting slope ~~($\tilde{c}_1$)~~ ($\tilde{c}_1$) shall be used. For the approximation of the second part, the end slope ~~($\tilde{c}_2$)~~ ($\tilde{c}_2$) shall be used. ~~Figure 3~~ Figure 3 illustrates the approximation procedure. The intersection of both lines gives parameter ~~$\tilde{D}_1$.~~ $\tilde{D}_1$.

The parameter values from the measured response curve shall then be compared with the parameter values from the reference response curve. Each shall apply to the following conditions:

~~(1) $\tilde{D}_1 \leq D_1$ (i.e., $\tilde{D}_1$ shall not exceed D_1 from the reference response curve)~~
~~(2) $\tilde{c}_1 \times \tilde{D}_1 \leq c_1 \times D_1$ (i.e., the product of $\tilde{c}_1$ and $\tilde{D}_1$ shall not exceed the product of c_1 and D_1)~~
~~(3) $\tilde{c}_2 \geq 0{,}75 \times c_2$ (i.e., $\tilde{c}_1$ shall be equal to or higher than 75% of c_2)~~

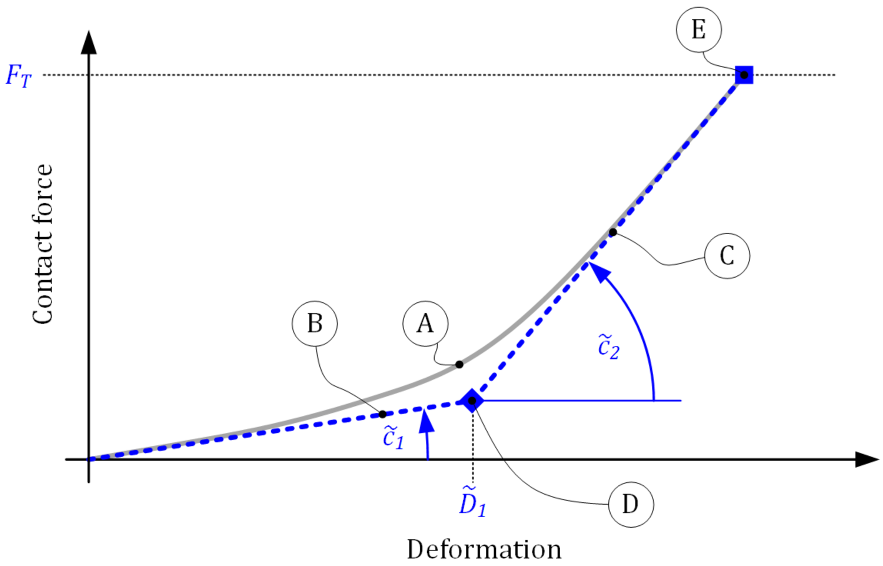
(1) $\tilde{D}_1 \leq D_1$ (i.e., $\tilde{D}_1$ shall not exceed D_1 from the reference response curve)

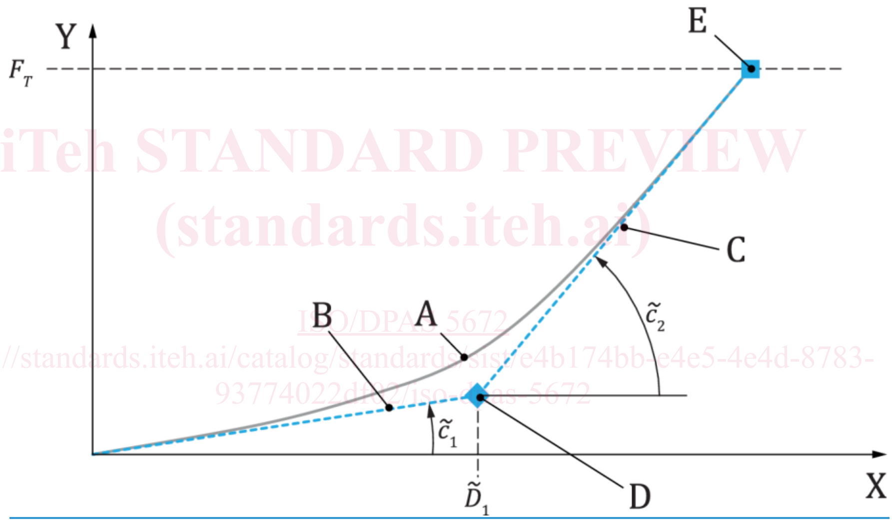
(2) $\tilde{c}_1 \times \tilde{D}_1 \leq c_1 \times D_1$ (i.e., the product of $\tilde{c}_1$ and $\tilde{D}_1$ shall not exceed the product of c_1 and D_1)

(3) $\tilde{c}_2 \geq 0{,}75 \times c_2$ (i.e., $\tilde{c}_1$ shall be equal to or higher than 75 % of c_2)

NOTE The slope of the first approximation line ~~($\tilde{c}_1$)~~ ($\tilde{c}_1$) taken from the measured response curve can be lower than ~~c_1.~~ c_1. It is, however, not recommended for avoiding a loss of robot efficiency. Same applies to the slope of the second approximation line ~~($\tilde{c}_2$)~~ ($\tilde{c}_2$) which can but should not exceed ~~c_2.~~ c_2.

According to conditions (1) and (2), it is acceptable not to replicate the flat part of the reference response curve (i.e., ~~$\tilde{D}_1 = 0$ and $\tilde{c}_1 = 0$).~~ $\tilde{D}_1 = 0$ and $\tilde{c}_1 = 0$). Omitting this part of the response curve can be necessary, when its replication is not possible because of technical constraints or other boundaries.





Key

AX Mechanical response curve measured with a PFMDdeformation

DC Intersection of the first and second linesecond line that has the end slope of the response curve where it intersects with the transient force limit (F_T)

Y contact force

D intersection of the first and second line

BA First line that has the starting slope of themechanical response curve measured with a PFMD

E Intersectionintersection of the second line with the transient force limit (F_T)(F_T)

CB Secondfirst line that has the endstarting slope of the response curve where it intersects with the transient force limit (F_T)measured

Figure 3 3 — Calibration parameters derived from a PFMD response curve