Technical Specification

ISO/TS 18571

Second edition
2024-05

Road vehicles — Objective rating metric for non-ambiguous signals

Véhicules routiers — Mesures pour l'évaluation objective de signaux non ambigus

Reference number
ISO/TS 18571:2024(en)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 36, *Safety and impact testing.*

This second edition cancels and replaces the first edition (ISO/TS 18571:2014), which has been technically revised.

The main changes are as follows:

— more descriptions about window size for dynamic time warping were provided. Ten percent of data length was used as window size;

— for slope score calculation, a modified algorithm was developed. In the new algorithm, a nine-point moving average method was used to keep data point symmetry and slope curve smooth;

— in original Annex data sets, some time intervals were not consistent with variations at thousandth digit. Now, data sets were cleaned up and time interval variations were eliminated. New rating results on Annex data sets were provided and all figures and tables were updated accordingly.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Computer Aided Engineering (CAE) has become a vital tool for product development in the automobile industry. Various computer programs and models have been developed to simulate dynamic systems. To maximize the use of these models, the validity and predictive capabilities of these models are assessed quantitatively. Model validation is the process of comparing CAE model outputs with test measurements in order to assess the validity or predictive capabilities of the CAE model for its intended usage. The fundamental concepts and terminology of model validation have been established mainly by standard committees including the American Institute of Aeronautics and Astronautics (AIAA)[2], the American Society of Mechanical Engineers (ASME) Standards Committees on verification and validation of Computational Solid Mechanics[3] and Computational Fluid Dynamics and Heat Transfer[4], the Defense Modeling and Simulation Office (DMSO) of the U.S. Department of Defense (DoD)[5], the United States Department of Energy (DOE)[6] and various other professional societies [19],[20].

One of the critical tasks to achieve quantitative assessments of models is to develop a validation metric that has the desirable metric properties to quantify the discrepancy between functional or time history responses from both physical test and simulation result of a dynamic system[7],[16],[17]. Developing quantitative model validation methods has attracted considerable researchers' interest in recent years [11],[12],[13],[15],[17],[18],[23],[24],[26]. However, the primary consideration in the selection of an effective metric should be based on the application requirements. In general, the validation metric is a quantitative measurement of the degree of agreement between the physical test and simulation results.

This document is the essential excerpt of the ISO/TR 16250[1] which provides standardized calculations of the correlation between two signals of dynamic systems, and it is validated against multiple vehicle safety case studies.

Road vehicles — Objective rating metric for non-ambiguous signals

1 Scope

This document provides validation metrics and rating procedures to calculate the level of correlation between two non-ambiguous signals obtained from a physical test and a computational model and it is aimed at vehicle safety applications. The objective comparison of time-history signals of model and test is validated against various loading cases under different types of physical loads such as forces, moments and accelerations. However, other applications can be possible too, but are not within the scope of this document.

NOTE Annex A gives some examples of the application of this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain 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
filtering
smoothing of signals by using standardized algorithms

3.2
level of correlation
similarity of two signals

3.3
interval of evaluation
time domain that is used to calculate the correlation between two signals

3.4
rating
calculated value that represents a certain *level of correlation* (3.2) (objective rating)

3.5
sampling rate
recording frequency of a signal

3.6
time sample
pair values (e.g. time and amplitude) of a recorded signal

3.7
time-history signal
physical value recorded in a time domain

Note 1 to entry: Time-history signals are non-ambiguous.

4 Abbreviated terms and symbols

4.1 Abbreviated terms

CAE	Computer Aided Engineering
CORA	CORrelation and Analysis
DTW	Dynamic Time Warping
EEARTH	Enhanced Error Assessment of Response Time Histories
SME	Subject Matter Expert

4.2 General

C , $C(t)$	Analyzed signal (CAE signal)
T , $T(t)$	Reference signal (test signal)
Δt	Interval between two-time samples
t	Time signal (axis of abscissa)
t_0	Time zero of an event (e.g. test, crash, impact)
t_{start}	Starting time of the interval of evaluation
t_{end}	Ending time of the interval of evaluation
N	Total number of sample points (e.g. time steps) between the starting time t_{start} and ending time t_{end}

4.3 Corridor score

Z	Corridor score
$Z(t)$	Corridor score at time t (curve)
k_Z	Exponent factor for calculating the corridor score between the inner and outer corridors
a_0	Relative half width of the inner corridor
b_0	Relative half width of the outer corridor
δ_i	Half width of the inner corridor
δ_o	Half width of the outer corridor
$\delta_i(t)$	Lower/upper bounds of the inner corridor at time t (curve)
$\delta_o(t)$	Lower/upper bounds of the outer corridor at time t (curve)

$N_{>0}$	All natural numbers without zero
T_{norm}	Absolute maximum amplitude of the reference signal T

4.4 Phase, magnitude and slope scores

4.4.1 General

C^{ts}, $C^{ts}(i)$	Truncated and shifted CAE curve
C^{ts+w}	Warped CAE curve of C^{ts}
C_0^{ts+d}	Derivative CAE curve of C^{ts}
C^{ts+d}	Derivative CAE curve of C^{ts} after averaging
T^{ts}, $T^{ts}(j)$	Truncated and shifted test curve
T^{ts+w}	Warped test curve of T^{ts}
T_0^{ts+d}	Derivative test curve of T^{ts}
T^{ts+d}	Derivative test curve of T^{ts} after averaging

4.4.2 Phase score

E_P	Phase score
k_P	Exponent factor for calculating the phase score E_P
ε_P^*	Maximum allowable percentage of time shift
m	Time steps moved to evaluate the phase error
n_ε	Number of time shifts to get ρ_E
ρ_E	Maximum cross correlation of all $\rho_L(m)$ and $\rho_R(m)$
$\rho_L(m)$	Cross correlation – signal is moved to the left
$\rho_R(m)$	Cross correlation – signal is moved to the right

4.4.3 Magnitude score

E_M	Magnitude score
k_M	Exponent factor for calculating the magnitude score E_M
ε_M^*	Maximum allowable magnitude error
ε_{mag}	Magnitude error
n	Number of data samples of time shifted and truncated curves (C^{ts} and T^{ts})

d	Local cost matrix to perform the dynamic time warping
$d(i, j)$	Local cost function to perform the dynamic time warping
$d_{tw}[i, j]$	Cumulative cost matrix
D_{TW}	Dynamic time warping distance
$D_{TWopt}(i, j)$	Cost of the optimal warping path
i	Index number of time shifted and truncated CAE curve C^{ts}
i_l	Index number of l-th warping path of curve C^{ts}
j	Index number of time shifted and truncated test curve T^{ts}
j_l	Index number of l-th warping path of curve T^{ts}
k	Index number of any warping path
$\tilde{k}$	Number of data samples of the optimal warping path
w	Optimal warping path
w_l	The l-th warping path cell

4.4.4 Slope score

E_S	Slope (topology) score
k_S	Exponent factor for calculating the slope score E_S
ε_S^*	Maximum allowable slope error
ε_{slope}	Slope error

4.5 Overall ISO rating

R	Overall ISO rating
w_Z	Weighting factor of the corridor score Z
w_P	Weighting factor of the phase score E_P
w_M	Weighting factor of the magnitude score E_M
w_S	Weighting factor of the slope score E_S
r	Rank of the sliding scale of the ISO metric
$S_{Clower}(r)$	Lower threshold of rank r
$S_{Cupper}(r)$	Upper threshold of rank r

5 General data requirements

The metric described in this document requires non-ambiguous curves (e.g. time-history curves). Furthermore, it is required that the reference curve $T(t)$ and the evaluated curve $C(t)$ are both defined between starting time t_{start} and ending time t_{end}. Both curves shall have the same number of sample points N with a constant time interval Δt within the evaluation interval.

6 ISO metric

6.1 General

The approach of this document is to combine different types of algorithms to get reliable and robust assessments of the correlation of two signals. The calculated score provides fair assessment for poor and for good correlations of two signals. The two most promising metrics are identified in Reference [1], they are the CORA corridor method and EEARTH. A combined metric based on the improved CORA corridor method and EEARTH is then proposed for this document which has been fully validated using responses from multiple vehicle passive safety applications.

Figure 6.1 shows the structure of the overall ISO metric. While the corridor method calculates the deviation between curves with the help of automatically generated corridors, the EEARTH method analyses specific curve characteristics such as phase shift, magnitude and shape. Hence, the ISO metric consists of the two best available algorithms.

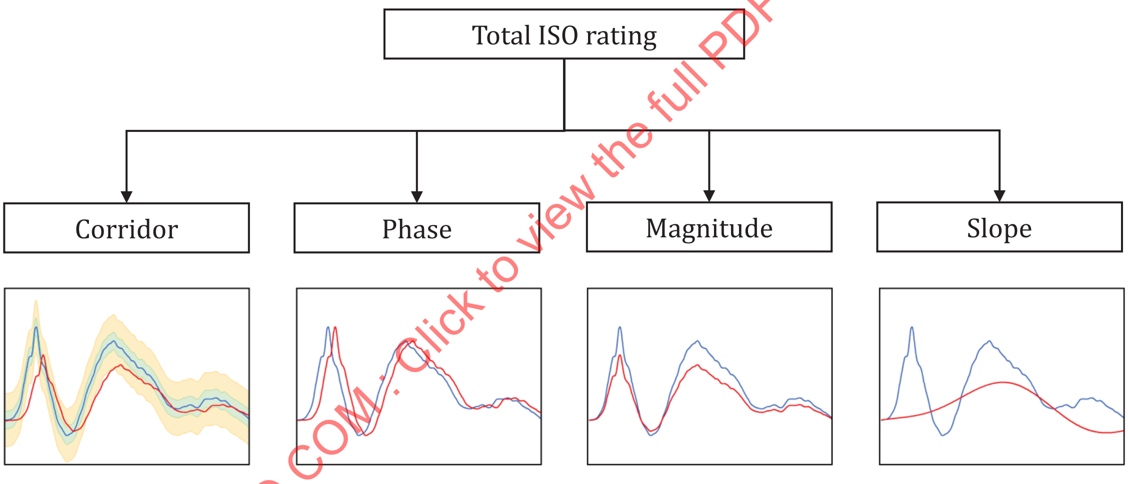


Figure 6.1 — ISO metric structure

6.2 Calculation of the overall ISO rating

The combination of the four metric ratings (corridor, phase, magnitude and slope) will provide a single number R for the correlation of the analysed signals which represents the final overall objective rating. The overall objective rating R is calculated by combining the separate sub-ratings of corridor (Z), phase (E_P), magnitude (E_M) and slope (E_S). Four individual weighting factors are defining the influence of each metric on the overall rating [see Formulae (6.1) and (6.2)]. The corresponding weighting factors are shown in Table 6.1.

$$R = w_Z \cdot Z + w_P \cdot E_P + w_M \cdot E_M + w_S \cdot E_S \quad (6.1)$$

$$w_Z + w_P + w_M + w_S = 1 \quad (6.2)$$

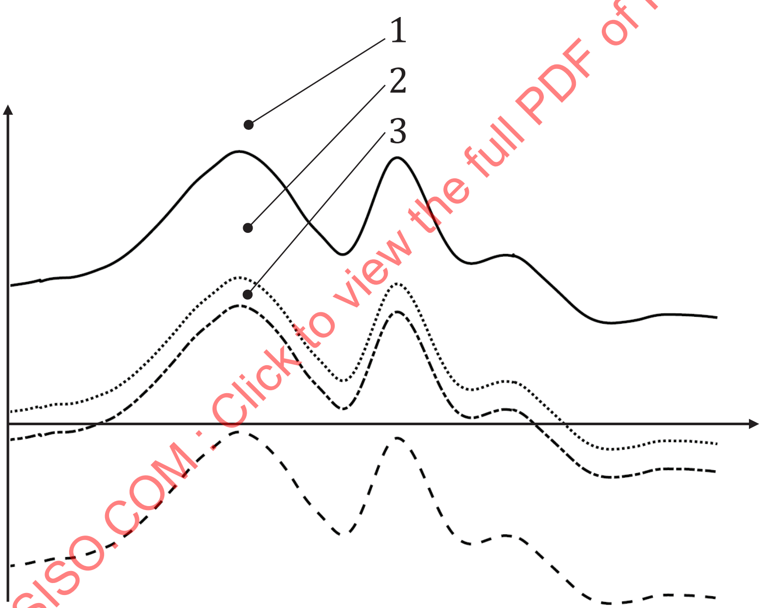
Table 6.1 — Weighting factors of the ISO sub-ratings

Parameter	Value	Description
w_Z	0,4	Weighting factor of the corridor score
w_P	0,2	Weighting factor of the phase score
w_M	0,2	Weighting factor of the magnitude score
w_S	0,2	Weighting factor of the slope score

6.3 Corridor score

6.3.1 General

The corridor metric calculates the deviation between two signals by means of corridor fitting. The two sets of corridors, the inner and the outer corridors, are defined along the mean curve. If the evaluated curve C is within the inner corridor bounds, a score of "1" is given and if it is outside the outer corridors bounds, the score is set to "0". The assessment declines from "1" to "0" between the bounds of inner and outer corridors resulting in three different rating zones as shown in Figure 6.2. The compliance with the corridors is calculated at each specific time t and the final corridor score Z of a signal is the average of all scores $Z(t)$ at specific times t.



Key

1 rating = 0

2 0 < rating < 0

3 rating = 1

Figure 6.2 — Rating zones of the corridor metric (corridors of constant width)[9]

The philosophy of the ISO approach is to use a narrow inner corridor and a wide outer corridor[14]. It limits the number of "1" ratings to only good correlations and gives the opportunity to distinguish between poor and fair correlations. If the outer corridor is too narrow, too many curves of a fair or moderate correlation would get the same poor rating of "0", like signals of almost no correlation with the reference. Basically, the width of the corridors can be adjusted in order to reflect the specific signal characteristic. The width can be constant for the whole duration of the dynamic responses or vary at the different time intervals. This document applies the most common approach of using constant corridor widths for the whole duration of the dynamic response[1],[25].

6.3.2 Calculation

The parameters a_0 and b_0 define the relative half widths of the inner and the outer corridors. Both shall be between "0" and "1", and a_0 shall be less than b_0. The absolute half widths of both corridors are defined as the product of relative half width and the absolute maximum amplitude T_{norm} of the reference signal T. Formula (6.3) shows the calculation of T_{norm} and it is calculated within the interval of evaluation.

$$T_{\text{norm}} = \max\{|\min(T)|, |\max(T)|\} \quad (6.3)$$

The absolute half width of the inner corridor (absolute distance from the reference signal to the outer bounds of the inner corridor) is defined by Formula (6.4). The calculation of the absolute half width of the outer corridors [see Formula (6.5)] is similar to that of the inner corridors.

$$\delta_{\text{i}} = a_0 \cdot T_{\text{norm}} \qquad 0 \le a_0 \le 1 \quad (6.4)$$

$$\delta_{\text{o}} = b_0 \cdot T_{\text{norm}} \qquad 0 \le b_0 \le 1 \quad \text{and} \quad a_0 < b_0 \quad (6.5)$$

Based on these definitions the lower and upper bounds of the inner corridor are defined by Formula (6.6) and the lower and upper bounds of the outer corridor are defined by Formula (6.7).

$$\delta_{\text{i}}(t) = T(t) \pm \delta_{\text{i}} \quad (6.6)$$

$$\delta_{\text{o}}(t) = T(t) \pm \delta_{\text{o}} \quad (6.7)$$

Formula (6.8) shows the calculation of the corridor score for the correlation between the reference signal T and the analysed signal C at each evaluation time t. If the absolute difference between the signals T and C is less than the half width of the inner corridor (δ_{i}), then the score is set to "1". The score is calculated by Formula (6.8) when the absolute difference between both signals is in between $\delta_{\text{i}} \le |T(t) - C(t)| \le \delta_{\text{o}}$. If the absolute difference between both signals is greater than the half width of the outer corridor (δ_{o}), then the score is set to "0". The parameter k_{Z} assesses the location of the analysed signal within the outer corridor, and it applies the appropriate penalty on the score. A linear ($k_{\text{Z}} = 1$), quadratic ($k_{\text{Z}} = 2$), cubical ($k_{\text{Z}} = 3$) or any other regression relationship can be defined accordingly.

$$Z(t) = \begin{cases} 1 & \text{if} \quad |T(t) - C(t)| < \delta_{\text{i}} \\ \left(\dfrac{\delta_{\text{o}} - |T(t) - C(t)|}{\delta_{\text{o}} - \delta_{\text{i}}} \right)^{k_{\text{Z}}} & \\ 0 & \text{if} \quad |T(t) - C(t)| > \delta_{\text{o}} \end{cases} \qquad k_{\text{Z}} \in N_{>0} \quad (6.8)$$

The final corridor score Z is calculated by averaging all single time step score $Z(t)$ as shown in Formula (6.9). The parameter N represents the total number of sample points (e.g. time steps) between starting and ending times of the interval of evaluation.

$$Z = \frac{\sum_{t=t_{\text{start}}}^{t_{\text{end}}} Z(t)}{N} \quad (6.9)$$

One of the advantages of the corridor metric is the simplicity and the clearness of the algorithm. It reflects criteria which are used intuitively in engineering judgment. Sometimes this simplicity may be the disadvantage of the method. For example, a small distortion of the phase can lead to a very undesirable rating[1].

Based on a sensitivity study of CORA[14] and as described in Reference [1], fixed width corridors are employed and the most appropriate metric parameters are identified as shown in Table 6.2.

Table 6.2 — Parameters of the corridor metric

Parameter	Value	Description
a_0	0,05	Relative half width of the inner corridor
b_0	0,50	Relative half width of the outer corridor
k_Z	2	Transition between ratings of “1” and “0” (progression)

6.3.3 Step by step procedure

First, the signals shall be pre-processed as described in Clause 8. After preparing the signals for the analysis and defining the interval of evaluation, the maximum absolute amplitude T_{norm} of the reference signal T shall be determined within this interval. It is used to calculate the inner and outer corridors. The actual corridor assessment shall be executed within this defined interval. The total score ranges between “0” and “1”. A score of “1” does not mean that both signals are identical. Solely their correlation is mathematically perfect within the defined tolerances.

To summarize, the following step-by-step procedures shall be followed to calculate corridor score:

a) Pre-process both signals according to Clause 8.

b) Calculate T_{norm} within the interval of evaluation by using the reference signal.

c) Calculate the inner and the outer corridors.

d) Calculate the corridor score $Z(t)$ at every specific time t within the interval of evaluation.

e) Calculate the total corridor score Z based on $Z(t)$ and the number N of time sample points.

6.4 Phase, magnitude and slope scores

Phase, magnitude and slope (or so-called topology) error assessments between the time history curves T and C are used as objective rating metrics[23],[27] in addition to the corridor metric described before. The enhanced error assessment of response time histories (EEARTH) metric combines these three assessments to the global response error[27]. It is defined as the error associated with the complete time history with equal weight on each point. Quantifying the errors associated with these features of phase, magnitude and slope (topology) separately is challenging because there are strong interactions among them. For example, to quantify the error associated with magnitude, the presence of a phase difference between the time histories may result in a misleading measurement. A unique feature dynamic time warping (DTW)[22] is used to separate the interaction of phase, magnitude and slope (topology) errors. It aligns peaks and valleys as much as possible by expanding and compressing the time axis according to a given cost (distance) function[9].

The ranges of the three errors are quite different and there is no single rating that can provide a quantitative assessment alone. Therefore, a numerical optimization method is employed to identify the appropriate parameters so that the resulted phase, magnitude and slope sub-ratings can match with SME’s ratings closely[8],[21]. Figure 6.3 shows the workflow of the procedures and the details of the algorithms are described in the following subsections.

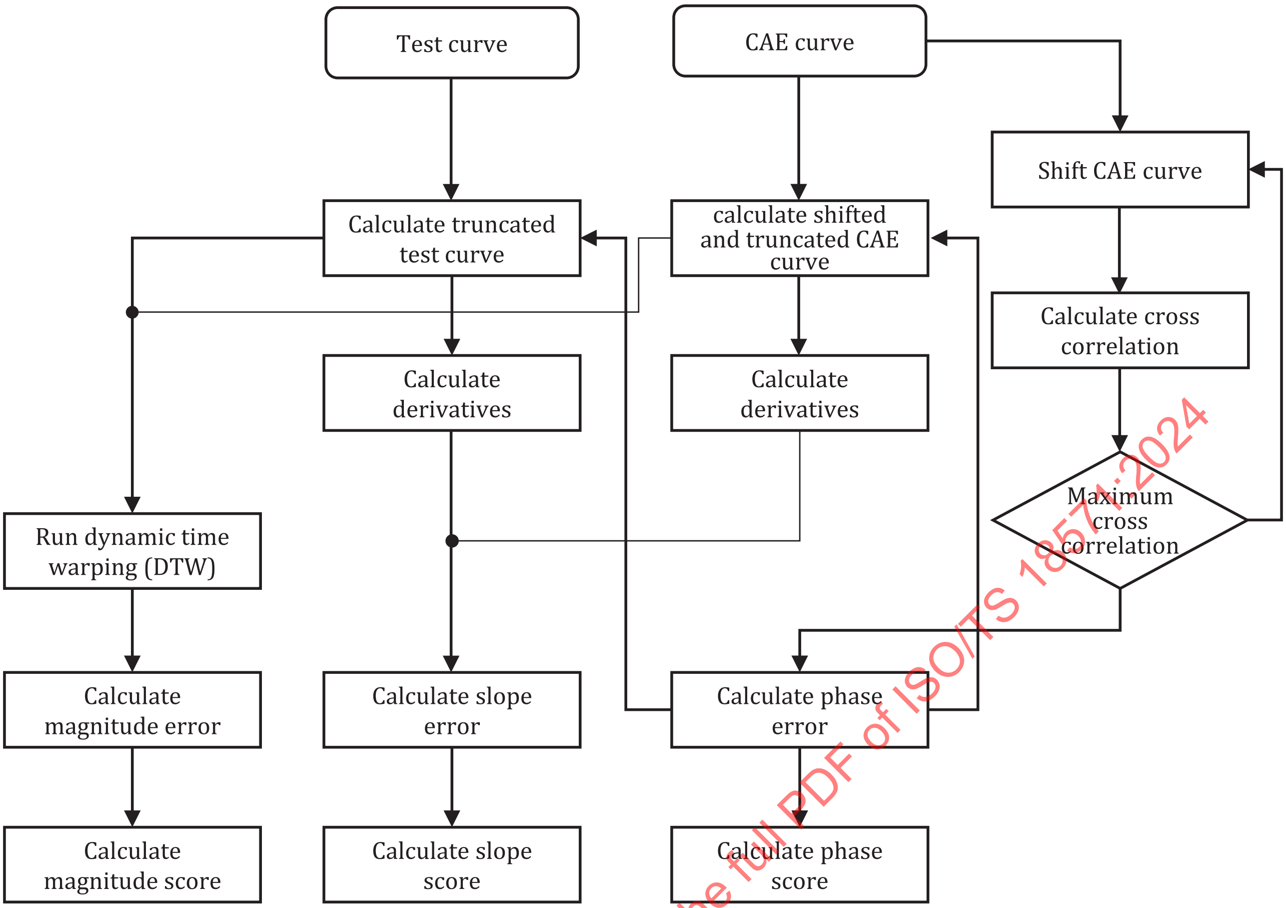


Figure 6.3 — Workflow of the calculation of phase, magnitude and slope scores

6.4.1 Phase score

The phase score E_P is used to measure the phase lag between the two-time histories T and C. The maximum allowable percentage of time shift is ε_P^* and it is pre-defined. In this step, the initial curve C is shifted left then right one step at a time to the original test data, curve T, and the cross correlation between the truncated test curve T, and shifted and truncated C are calculated until reaching the maximum allowable time shift limits $\varepsilon_P^* \cdot (t_{end} - t_{start})$.

When the initial curve C is moved to the left by m time steps, the number of overlapping points of the two time histories after time shift $m \cdot \Delta t$ is reduced to n ($n = N - m$) and the corresponding cross correlation value $\rho_L(m)$ is calculated by Formula (6.10).

$$\rho_L(m) = \frac{\sum_{i=0}^{n-1}[(C(t_{start} + (m+i) \cdot \Delta t) - \bar{C}(t)) \cdot (T(t_{start} + i \cdot \Delta t) - \bar{T}(t))]}{\sqrt{\sum_{i=0}^{n-1}[C(t_{start} + (m+i) \cdot \Delta t) - \bar{C}(t)]^2} \cdot \sqrt{\sum_{i=0}^{n-1}[T(t_{start} + i \cdot \Delta t) - \bar{T}(t)]^2}} \quad (6.10)$$

When the initial curve C is moved to the right by m time steps, the number of overlapping points after time shift $m \cdot \Delta t$ is reduced to n ($n = N - m$) and the corresponding cross correlation value $\rho_R(m)$ is calculated by Formula (6.11)

$$\rho_R(m) = \frac{\sum_{i=0}^{n-1}[(C(t_{start} + i \cdot \Delta t) - \bar{C}(t)) \cdot (T(t_{start} + (m+i) \cdot \Delta t) - \bar{T}(t))]}{\sqrt{\sum_{i=0}^{n-1}[C(t_{start} + i \cdot \Delta t) - \bar{C}(t)]^2} \cdot \sqrt{\sum_{i=0}^{n-1}[T(t_{start} + (m+i) \cdot \Delta t) - \bar{T}(t)]^2}} \quad (6.11)$$

The maximum cross correlation ρ_E is the maximum of all $\rho_L(m)$ and $\rho_R(m)$. If $\rho_L(m)$ and $\rho_R(m)$ result in the same value as maximum use the one which results from less time shifting steps. If time shifting is also the same, prioritize $\rho_L(m)$. The number of the time shifting steps that yields the maximum cross correlation ρ_E is defined as the phase error n_ε. The corresponding shifted and truncated CAE curve C is recorded as C^{ts} and the corresponding truncated test curve is recorded as T^{ts}.

The phase score E_P is calculated by Formula (6.12). The best phase score is "1", which means there is no need to shift the CAE curve to reach the maximum cross correlation between the initial test and CAE curves. If the time shift n_ε is equal to or greater than the maximum allowable time shift threshold $\varepsilon_P^* \cdot N$, then the phase score is "0". In between, the phase score is calculated by a regression method. It is either linear ($k_P = 1$), quadratic ($k_P = 2$), or cubical ($k_P = 3$).

$$E_P = \begin{cases} 1 & \text{if} \quad n_\varepsilon = 0 \\ \left(\dfrac{\varepsilon_P^* \cdot N - n_\varepsilon}{\varepsilon_P^* \cdot N}\right)^{k_P} & \\ 0 & \text{if} \quad n_\varepsilon \geq \varepsilon_P^* \cdot N \end{cases} \qquad k_P \in \{1, 2, 3\} \quad (6.12)$$

The pre-defined parameters shown in Table 6.3 are identical to the definition in Reference [1].

Table 6.3 — Fixed parameters of the phase score

Parameter	Value	Description
k_P	1	Exponent factor for calculating the phase score
ε_P^*	0,2	Maximum allowable percentage of time shift

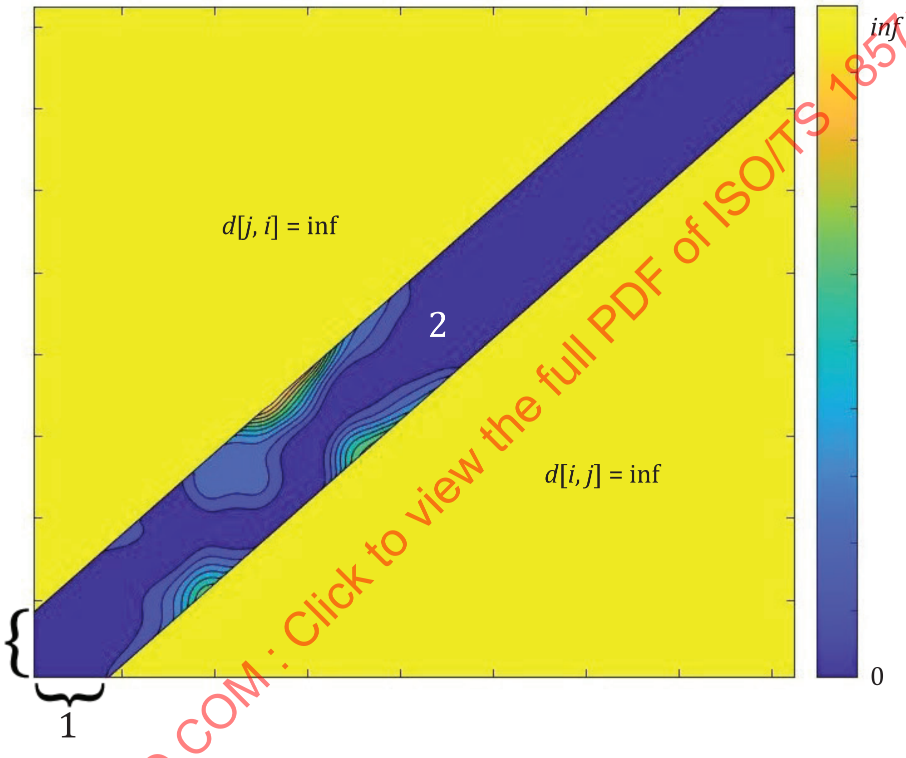
6.4.2 Magnitude score

The magnitude error is a measure of discrepancy in the amplitude of the two time histories. It is defined as the difference in amplitude of the two time histories when there is no time lag between them. Before calculating the magnitude error, the difference between the time histories caused by error in phase and slope (topology) are minimized by using dynamic time warping (DTW).

The definition of DTW is based on the notion of warping path. Let d be the matrix $n \times n$ of pair-wise squared distances between samples of C^{ts} and T^{ts}. This matrix d is called the local cost matrix. The function used to calculate the value for each cell of the matrix is called local cost function $d(i,j)$. It is shown in Formula (6.13).

$$d(i,j)=\begin{cases} \text{inf}, & i \geq j+\text{ceil}(0{,}1 * N) \\ \text{inf}, & j \geq i+\text{ceil}(0{,}1 * N) \\ \left(C^{ts}(i)-T^{ts}(j)\right)^2, & \text{otherwise} \end{cases} \quad (6.13)$$

Where ceil means ceiling function. To make sure dynamic warping is within a reasonable range, maximum allowed warping window is defined as 10 % length of the shifted and truncated curve. Any local cost function falls outside this area will be set as infinite value as following Figure 6.4 shows.



Key

1 window size

2 acceptable warping band

Figure 6.4 — Cost function for allowable DTW window

Once the local cost matrix is built, the algorithm finds the alignment path which runs through the low-cost areas on the cumulated cost matrix. A warping path w_K [Formula (6.14)] is a sequence of k matrix cells [Formula (6.15)].

$$w_K = \langle w_1, w_2, \ldots, w_k \rangle \qquad n \leq k \leq (2n-1) \quad (6.14)$$

$$w_l = [i_l, j_l] \qquad 1 \le l \le k \tag{6.15}$$

The cost of the warping path shall meet the following three conditions:

— Boundary conditions

$w_1 = [1,1]$ and $w_k = [n,n]$, i.e. w starts in the lower left cell and ends in the upper right cell.

— Continuity

Given $w_{l-1} = [i_{l-1}, j_{l-1}]$ and $w_l = [i_l, j_l]$, then, $i_l - i_{l-1} \le 1$ and $j_l - j_{l-1} \le 1$. This ensures that the cells of the warping path are adjacent.

— Monotonicity

Given $w_{l-1} = [i_{l-1}, j_{l-1}]$ and $w_l = [i_l, j_l]$, then, $i_l - i_{l-1} \ge 0$ and $j_l - j_{l-1} \ge 0$, with at least one strict inequality. This enforces w to progress over time.

The DTW distance is recursively computed using a dynamic programming approach that fills the cells of a cumulative cost matrix $d_{\text{tw}}[i,j]$ and recurrence relation [Formula (6.16)]. The given sequence of d_{twmin} is mandatory if the values of the minima are the same. Then the DTW distance is evaluated as shown in Formula (6.17).

$$d_{\text{tw}}[i,j] = \begin{cases} d(i,j) & i=1, j=1 \\ d(i,j) + d_{\text{tw}}[i,j-1] & i=1 \\ d(i,j) + d_{\text{tw}}[i-1,j] & j=1 \\ d(i,j) + d_{\text{twmin}} & \text{otherwise} \end{cases} \{ \tag{6.16}$$

Where $d_{\text{twmin}} = \min(d_{\text{tw}}[i-1,j], d_{\text{tw}}[i,j-1], d_{\text{tw}}[i-1,j-1])$

$$D_{\text{TW}} = d_{\text{tw}}[n,n] \tag{6.17}$$

The warping path which has a minimal cost associated with alignment is called the optimal warping path. It is found by following the definition that every possible warping path between C^{ts} and T^{ts} should be tested which could be computationally challenging due to the exponential growth of the number of optimal paths as the lengths of C^{ts} and T^{ts} grow linearly.

Any warping path w_{K} defines an alignment between C^{ts} and T^{ts} and, consequently, a cost to align the two histories. $D_{\text{TWopt}}\left(C^{\text{ts}}, T^{\text{ts}}\right)^2$ is the minimum of such costs, i.e. the cost of the optimal warping path [Formula (6.18)].

$$D_{\text{TWopt}}\left(C^{\text{ts}}, T^{\text{ts}}\right)^2 = \min_{w_{\text{K}}}\left(\sum_{[i_l, j_l] \in w_{\text{K}}} d(i_l, j_l)\right) \tag{6.18}$$

Let i_l and j_l represent the index of warping path of CAE and test data. An optimal warping path index w is formed as shown in Formula (6.19) with $\tilde{k}$ steps in the path. It starts with $i_{\tilde{k}} = n$ and $j_{\tilde{k}} = n$, then it records each time step from $[n,n]$ to $[1,1]$. The algorithms can be expressed as shown in Formula (6.20).

$$w = \begin{bmatrix} i_{\tilde{k}} & i_{\tilde{k}-1} & \dots & i_l & \dots & i_1 \\ j_{\tilde{k}} & j_{\tilde{k}-1} & \dots & j_l & \dots & j_1 \end{bmatrix}^T \qquad 1 \le l \le \tilde{k} \tag{6.19}$$

$$[i_{l-1}, j_{l-1}] = \begin{cases} [i_l - 1, 1] & j_l = 1 \\ [1, j_l - 1] & i_l = 1 \\ [i_l - 1, j_l] & d_{tw}[i_l - 1, j_l] = d_{tw\,min} \\ [i_l, j_l - 1] & d_{tw}[i_l, j_l - 1] = d_{tw\,min} \\ [i_l - 1, j_l - 1] & d_{tw}[i_l - 1, j_l - 1] = d_{tw\,min} \end{cases} \tag{6.20}$$

Where $d_{twmin} = \min(d_{tw}[i-1, j], d_{tw}[i, j-1], d_{tw}[i-1, j-1])$. Hence, the index matrix of warping path w can be expressed by the index of CAE (C^{ts}) and test (T^{ts}) curves.

Then the truncated and warped CAE curve C^{ts+w} and the shifted, truncated, and warped test curve T^{ts+w} are formed as shown in Formulae (6.21) and (6.22).

$$\left[C^{ts+w}(i_{\tilde{k}}), C^{ts+w}(i_{\tilde{k}-1}), ..., C^{ts+w}(i_1)\right] = \left[C^{ts}(n), C^{ts}(n-1), ..., C^{ts+w}(1)\right] \quad C^{ts+w} \in \Re^{\tilde{k}} \tag{6.21}$$

$$\left[T^{ts+w}(j_{\tilde{k}}), T^{ts+w}(j_{\tilde{k}-1}), ..., T^{ts+w}(j_1)\right] = \left[T^{ts}(n), T^{ts}(n-1), ..., T^{ts+w}(1)\right] \quad T^{ts+w} \in \Re^{\tilde{k}} \tag{6.22}$$

The magnitude error ε_{mag} is calculated by Formula (6.23).

$$\varepsilon_{mag} = \frac{\left\| C^{ts+w} - T^{ts+w} \right\|_1}{\left\| T^{ts+w} \right\|_1} \tag{6.23}$$

Formula (6.24) is used to calculate the magnitude score E_M, where ε_M^* is the maximum allowable magnitude error and k_M defines the order of the regression. The best magnitude score is “1”, which means there is no difference in the amplitudes after phase shift and dynamic time warping. If the magnitude error ε_{mag} is equal to or greater than the maximum allowable magnitude error threshold ε_M^*, then the magnitude score is “0”. In between, the magnitude score is calculated by regression method.

$$E_M = \begin{cases} 1 & \text{if} \quad \varepsilon_{mag} = 0 \\ \left(\dfrac{\varepsilon_M^* - \varepsilon_{mag}}{\varepsilon_M^*} \right)^{k_M} & \qquad k_M \in \{1, 2, 3\} \\ 0 & \text{if} \quad \varepsilon_{mag} \geq \varepsilon_M^* \end{cases} \tag{6.24}$$

The pre-defined parameters shown in Table 6.4 are identical to the definition in Reference [1].

Table 6.4 — Fixed parameters of the magnitude score

Parameter	Value	Description
k_M	1	Exponent factor for calculating the magnitude score
ε_M^*	0,5	Maximum allowable magnitude error

6.4.3 Slope score

The slope error is a measure of discrepancy in slope (topology) of the two time histories. The slope of a time history is defined by the slope at each point. To ensure that the effect of global time shift is minimized, the slope is calculated from the time shifted histories T^{ts} and C^{ts}.

Central differences are first used to calculate the slope, except the first point taking a forward difference and the last point taking a backward difference.

$$C_0^{\text{ts+d}} = \begin{cases} \left(C^{\text{ts}}(i+1) - C^{\text{ts}}(i)\right)/\Delta t & \text{if} \quad i=1 \\ \left(C^{\text{ts}}(i+1) - C^{\text{ts}}(i-1)\right)/2\Delta t & \text{if} \quad 1<i<n \\ \left(C^{\text{ts}}(i) - C^{\text{ts}}(i-1)\right)/\Delta t & \text{if} \quad i=n \end{cases} \tag{6.25}$$

$$T_0^{\text{ts+d}} = \begin{cases} \left(T^{\text{ts}}(i+1) - T^{\text{ts}}(i)\right)/\Delta t & \text{if} \quad i=1 \\ \left(T^{\text{ts}}(i+1) - T^{\text{ts}}(i-1)\right)/2\Delta t & \text{if} \quad 1<i<n \\ \left(T^{\text{ts}}(i) - T^{\text{ts}}(i-1)\right)/\Delta t & \text{if} \quad i=n \end{cases} \tag{6.26}$$

Next, the average slope is calculated with a continuous nine-point interval to generate smoother slope curves ($C^{\text{ts+d}}$ and $T^{\text{ts+d}}$).

$$C^{\text{ts+d}} = \begin{cases} C_0^{\text{ts+d}}(i) & \text{if} \quad i=1,n \\ \frac{1}{3}\sum_{k=i-1}^{i+1} C_0^{\text{ts+d}}(k) & \text{if} \quad i=2,n-1 \\ \frac{1}{5}\sum_{k=i-2}^{i+2} C_0^{\text{ts+d}}(k) & \text{if} \quad i=3,n-2 \\ \frac{1}{7}\sum_{k=i-3}^{i+3} C_0^{\text{ts+d}}(k) & \text{if} \quad i=4,n-3 \\ \frac{1}{9}\sum_{k=i-4}^{i+4} C_0^{\text{ts+d}}(k) & \text{if} \quad 4<i<n-3 \end{cases} \tag{6.27}$$

$$T^{\text{ts+d}} = \begin{cases} T_0^{\text{ts+d}}(i) & \text{if} \quad i=1,n \\ \frac{1}{3}\sum_{k=i-1}^{i+1} T_0^{\text{ts+d}}(k) & \text{if} \quad i=2,n-1 \\ \frac{1}{5}\sum_{k=i-2}^{i+2} T_0^{\text{ts+d}}(k) & \text{if} \quad i=3,n-2 \\ \frac{1}{7}\sum_{k=i-3}^{i+3} T_0^{\text{ts+d}}(k) & \text{if} \quad i=4,n-3 \\ \frac{1}{9}\sum_{k=i-4}^{i+4} T_0^{\text{ts+d}}(k) & \text{if} \quad 4<i<n-3 \end{cases} \tag{6.28}$$

Therefore, the slope curves are in same length with time shifted history curves and are used to calculate the slope error directly without performing dynamic time warping. Both curves are then used to calculate the slope error $\varepsilon_{\text{slope}}$ by Formula (6.29).

$$\varepsilon_{\text{slope}} = \frac{\left\| C^{\text{ts+d}} - T^{\text{ts+d}} \right\|_1}{\left\| T^{\text{ts+d}} \right\|_1} \tag{6.29}$$

Formula (6.30) is used to calculate the slope score E_{S}, where ε_{S}^* is the maximum allowable slope error and k_{S} defines the order of the regression. The best slope score is "1", which means there is no difference between the two curve's slope. If the slope error $\varepsilon_{\text{slope}}$ is equal to or greater than the maximum allowable slope error $\varepsilon_{\text{S}}^{*}$, then the slope score is "0". In between, the slope score is calculated by regression method.

$$E_{\text{S}} = \begin{cases} 1 & \text{if} \quad \varepsilon_{\text{slope}} = 0 \\ \left(\dfrac{\varepsilon_{\text{S}}^{*} - \varepsilon_{\text{slope}}}{\varepsilon_{\text{S}}^{*}} \right)^{k_{\text{S}}} & \\ 0 & \text{if} \quad \varepsilon_{\text{slope}} \geq \varepsilon_{\text{S}}^{*} \end{cases} \qquad k_{\text{S}} \in \{1,2,3\} \tag{6.30}$$

The pre-defined parameters shown in Table 6.5 are identical to the definition in Reference [1].

Table 6.5 — Fixed parameters of the slope score

Parameter	Value	Description
k_{S}	1	Exponent factor for calculating the slope score
$\varepsilon_{\text{S}}^{*}$	2,0	Maximum allowable slope error

6.4.4 Step by step procedure

The following step by step process shall be followed to calculate the phase, magnitude and slope sub-ratings.

a) Pre-process both signals according to Clause 8 (C and T).

b) Calculate the phase error in terms of time steps n_{ε} by maximizing cross correlation.

c) Calculate the phase score E_{P}.

d) Calculate the shifted and truncated time history curves C^{ts} and T^{ts}.

e) Perform dynamic time warping to the shifted and truncated time history curves to generate the shifted, truncated and warped time history curves $C^{\text{ts+w}}$ and $T^{\text{ts+w}}$.

f) Calculate the magnitude error ε_{mag} between $C^{\text{ts+w}}$ and $T^{\text{ts+w}}$.

g) Calculate the magnitude score E_{M}.

h) Generate the shifted and truncated derivative time history curves $C_0^{\text{ts+d}}$ and $T_0^{\text{ts+d}}$.

i) Generate the smoother shifted and truncated derivative time history curves $C^{\text{ts+d}}$ and $T^{\text{ts+d}}$ by averaging nine-point intervals.

j) Calculate the slope error $\varepsilon_{\text{slope}}$ between $C^{\text{ts+d}}$ and $T^{\text{ts+d}}$.

k) Calculate the slope score E_{S}.

7 Meaning of the overall ISO rating

The objective rating R ranges from "0" to "1". The higher the score the better the correlation of the two signals. This single-rating number can be transferred to a grade that represents the level of the correlation by using a sliding scale (see Table 7.1).

Table 7.1 — Sliding scale of the overall ISO rating

Rank r	Grade	Rating R	Description
1	Excellent	$R > 0{,}94$	Almost perfect characteristics of the reference signal is captured
2	Good	$0{,}80 < R \leq 0{,}94$	Reasonably good characteristics of the reference signal is captured, but there are noticeable differences between both signals
3	Fair	$0{,}58 < R \leq 0{,}80$	Basic characteristics of the reference signal is captured but there are significant differences between the two signals
4	Poor	$R \leq 0{,}58$	Almost no correlation between the two signals

The lower and upper bounds of the different scales are calculated by using Formulae (7.1) and (7.2). Every grade is bounded by $\left(S_{\text{Clower}}(r), S_{\text{Cupper}}(r)\right]$ except the fourth grade "Poor" because there is no lower threshold $S_{\text{Clower}}(r=4)$ defined.

$$S_{\text{Clower}}(r) = 1 - \frac{1}{25}r^2 - \frac{1}{50}r \qquad r \in \{1,2,3\} \tag{7.1}$$

$$S_{\text{Clower}}(r) = 1 - \frac{1}{25}(r-1)^2 - \frac{1}{50}(r-1) \qquad r \in \{1,2,3,4\} \tag{7.2}$$

However, the thresholds of R in each grade are only valid if none of the parameters (e.g. weighting factors, regression schemes, sampling rates) described in the previous sections are altered.

8 Pre-processing of the data

8.1 General

During the evaluation and validation of the ISO metric, it was concluded that basic conditions for the compared signals such as, starting and ending times of the signals, sampling rate and filtering class shall be kept the same in order to obtain correct results. This shall be done by the user.

8.2 Synchronization of the signals

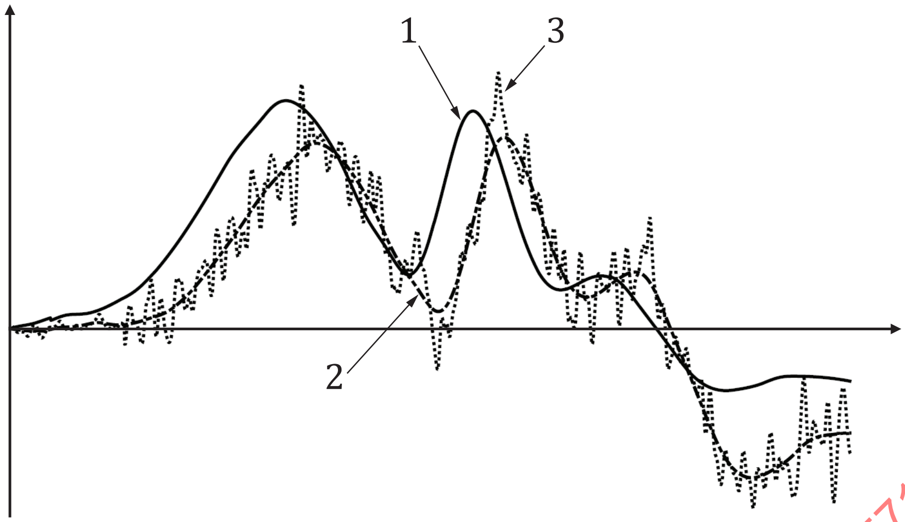
Initially, the signals shall be synchronized by physical meanings (t_0) and by its timing. At each time step of the test signal, a value of the CAE signal is required.

8.3 Sampling rate

The ISO metric was validated with signals of 10 kHz sampling rate. The sub-metrics to evaluate magnitude and slope are sensitive to the signal's sampling rate.

8.4 Filtering

The algorithms do not modify the original signals. It should be noted that the calculation of the correlation could be difficult when using noisy signals. Figure 8.1 shows an example of the filtering effect. Signals A and B are derived from the same unfiltered signal and differ only by the applied filter class. The overall correlation rating of signal B increased compared to that of signal A due to the application of a higher filter class. High-frequency oscillations could lead to misleading results.



Key

1 reference

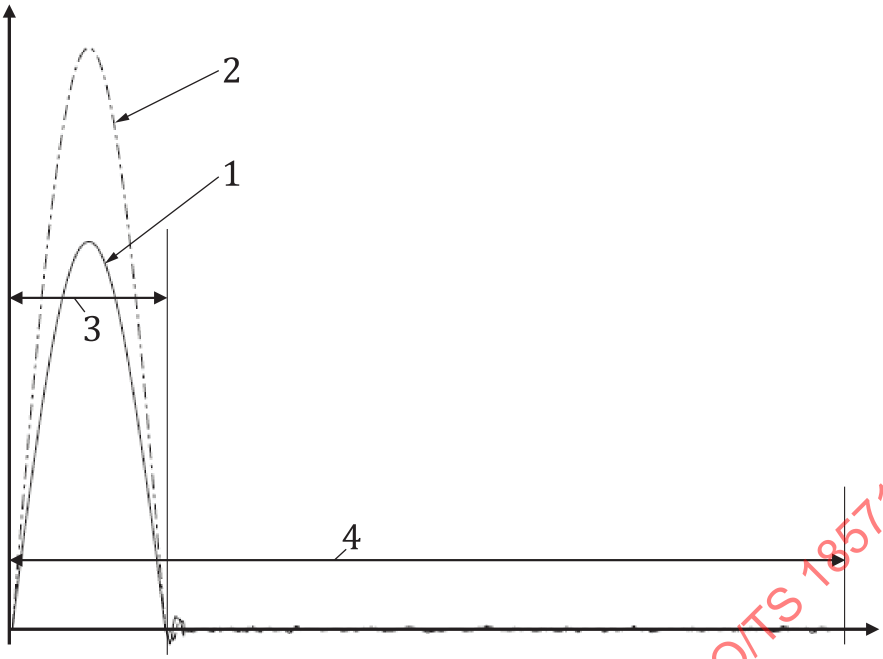
2 signal A (filter class 1)

3 signal B (filter class 2)

Figure 8.1 — Signals with different filter classes[10]

8.5 Interval of evaluation

The assessment of the correlation should be focused on the relevant parts of the given signals. Typically, crash signals include pre- and post-crash phases that are not of interest and should be excluded from the rating calculation. Therefore, an interval of evaluation shall be defined where the part of the signals is to be assessed. The interval starts at t_{start} and ends at t_{end}. An assessment of using ratings of different sub-intervals of the same pair of signals is not allowed.



Key
1 reference
2 signal A
3 relevant interval
4 complete signal

Figure 8.2 — Different intervals of evaluation[10]

Figure 8.2 depicts an example of this problem. The correlation rating is increased by 35 % when extending the interval of evaluation from the relevant part to the whole time domain.

The ISO metric requires a minimum length of the interval of evaluation of 10 ms.

9 Limitations

9.1 General

This document describes a method to apply an objective metric to calculate the level of the correlation between two signals. As previously described, the application of such a metric requires some basic conditions. Below is a list of a few known limitations to be considered when applying this metric.

9.2 Type of signals

The application of this metric is limited to non-ambiguous signals obtained in all kinds of tests of the passive safety of vehicles and the corresponding numerical simulations (CAE). The most commonly used signals in this field are time-history curves.

9.3 Metric validation

The metric is validated with time-history signals obtained from different data channel types such as, forces, moments, accelerations, velocities and displacements. It is also validated with time-history signals of various correlation qualities.

9.4 Meaning of the results

As described in this document, the presented sliding scale (see Clause 7) is only valid for the comparison of two signals. Any modification to the parameters such as weighting factors, sampling rates, etc. requires a revision of the grade's thresholds. Furthermore, the defined scale shall only be applied to the overall objective rating R and not to its metrics.

9.5 Multiple responses

This ISO metric is defined to calculate the level of the level of correlation between two signals only. If more than one pair of signals (e.g. whole set of signals from various channels of a test) are considered, the defined thresholds of the sliding scale are no longer valid.

Annex A
(informative)

Case studies

A.1 General

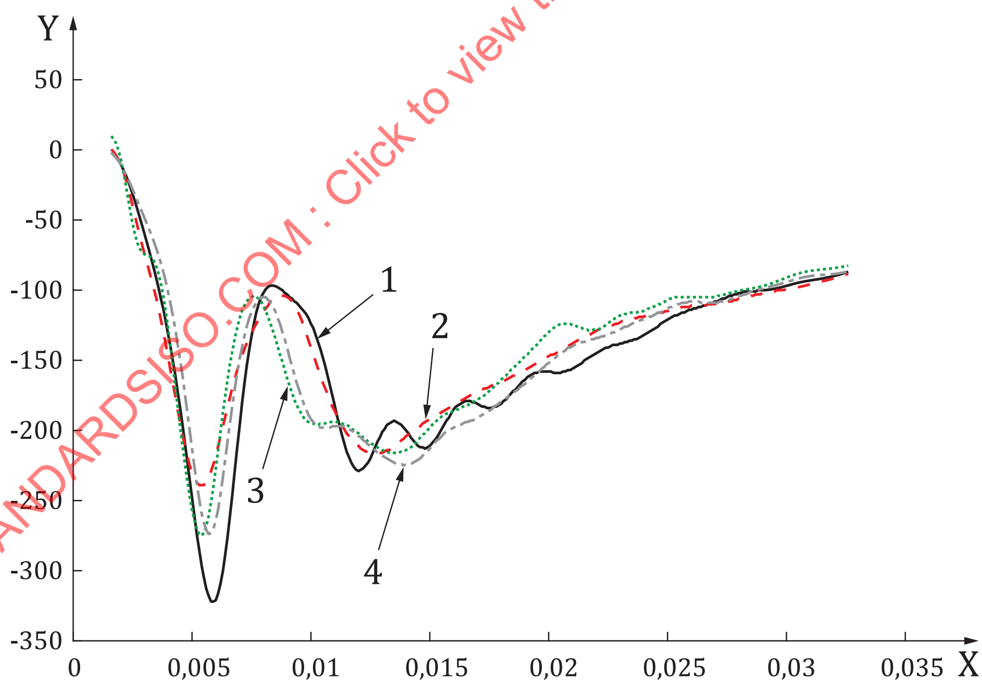
This annex gives some examples of the application of this document. It is very similar to ISO/TR 16250:2013, Annex C but shows intermediate result curves too. All responses are obtained in various tests related to passive safety of vehicles. The focus is on filtered and anonymized dummy responses. In each case three CAE signals are compared with a test signal. As the quality of the CAE signals differs, different levels of correlation are covered by these case studies. See Figures A.2.1 to A.6.16 and Tables A.2.1 to A.6.3.

When users develop their own code and apply Formula (6.20) searching for the warping path, if there are more than one path with same d_{tw} values among those three, always take the minimum one in following sequence: $d_{tw}[i-1,j]$, $d_{tw}[i,j-1]$, $d_{tw}[i-1,j-1]$.

When users compare their score results with the data provided in this annex, it is recommended that the differences between each corresponding component score should be within $\pm 0{,}001$ tolerance.

A.2 Accelerations

A.2.1 Acceleration 1



Key

X t, time [s]

Y a, acceleration [m/s[2]]

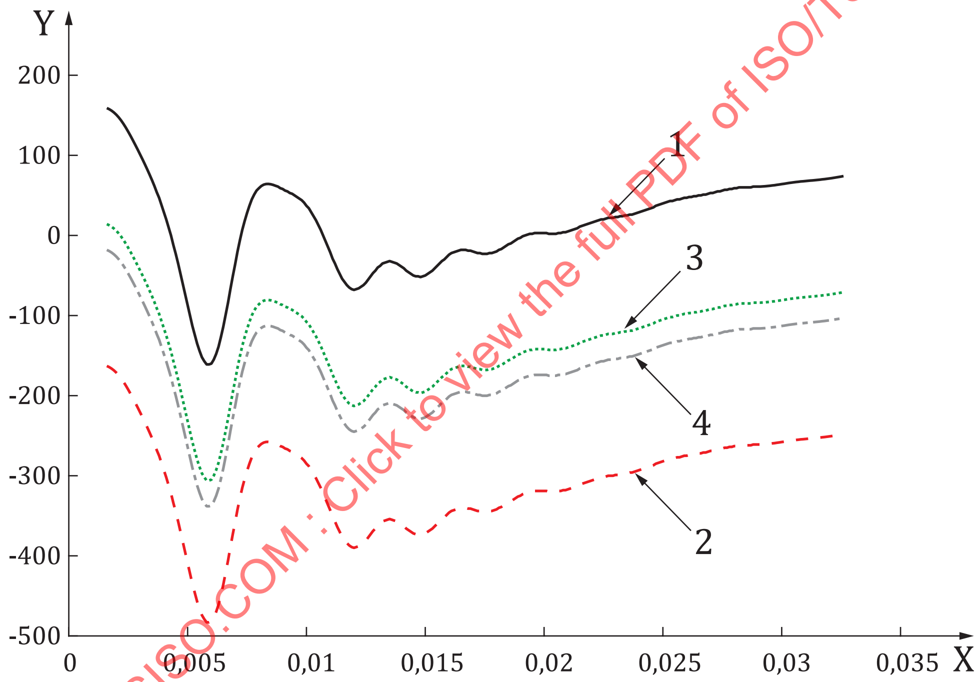
1 test

2 CAE1
3 CAE2
4 CAE3

Figure A.2.1 — Original curves

Table A.2.1 — ISO rating results

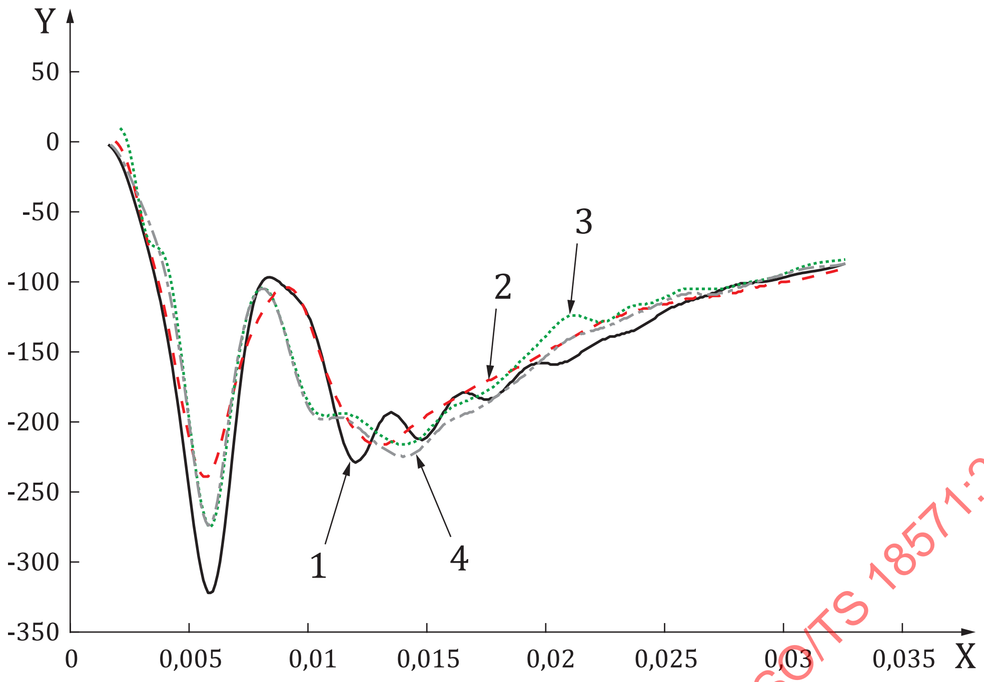
	CAE1 (C_1)	CAE2 (C_2)	CAE3 (C_3)
Grade	Good	Good	Good
Overall rating R	0,916 9	0,884 8	0,912 2
Corridor score Z	0,956 0	0,897 7	0,922 5
Phase score E_P	0,951 8	0,919 6	0,983 9
Magnitude score E_M	0,952 4	0,964 0	0,971 6
Slope score E_S	0,768 3	0,744 9	0,760 6



Key

X t, time [s]
Y a, acceleration [m/s^2]
1 outer corridor upper
2 outer corridor lower
3 inner corridor upper
4 inner corridor lower

Figure A.2.2 — Corridor curves



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

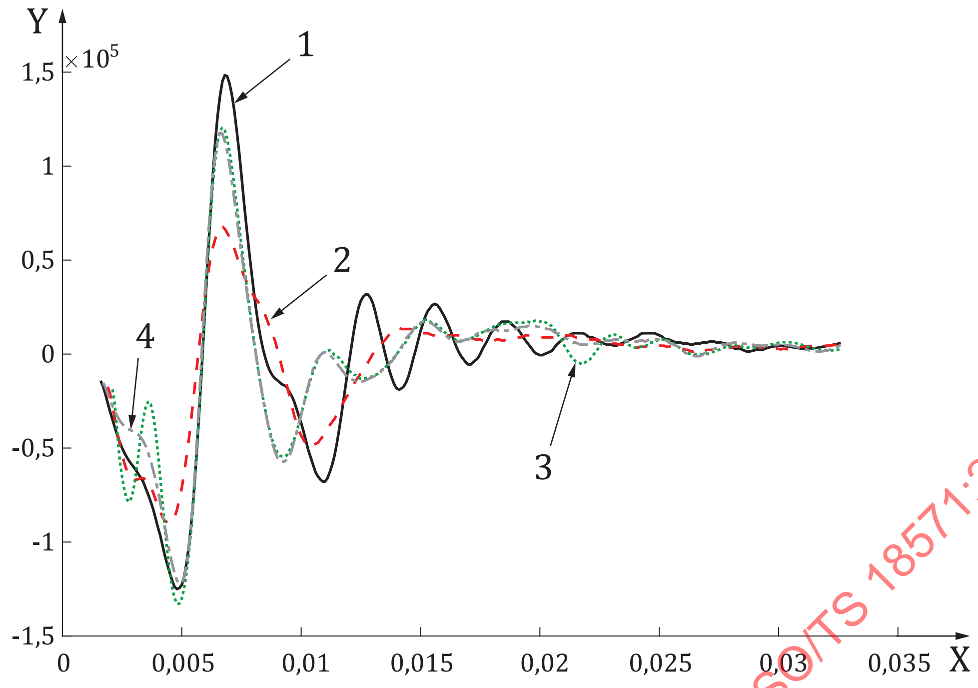
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.2.3 — Time shifted curves



Key

X *t*, time [s]

Y *s*, slope of acceleration curve[m/s^3]

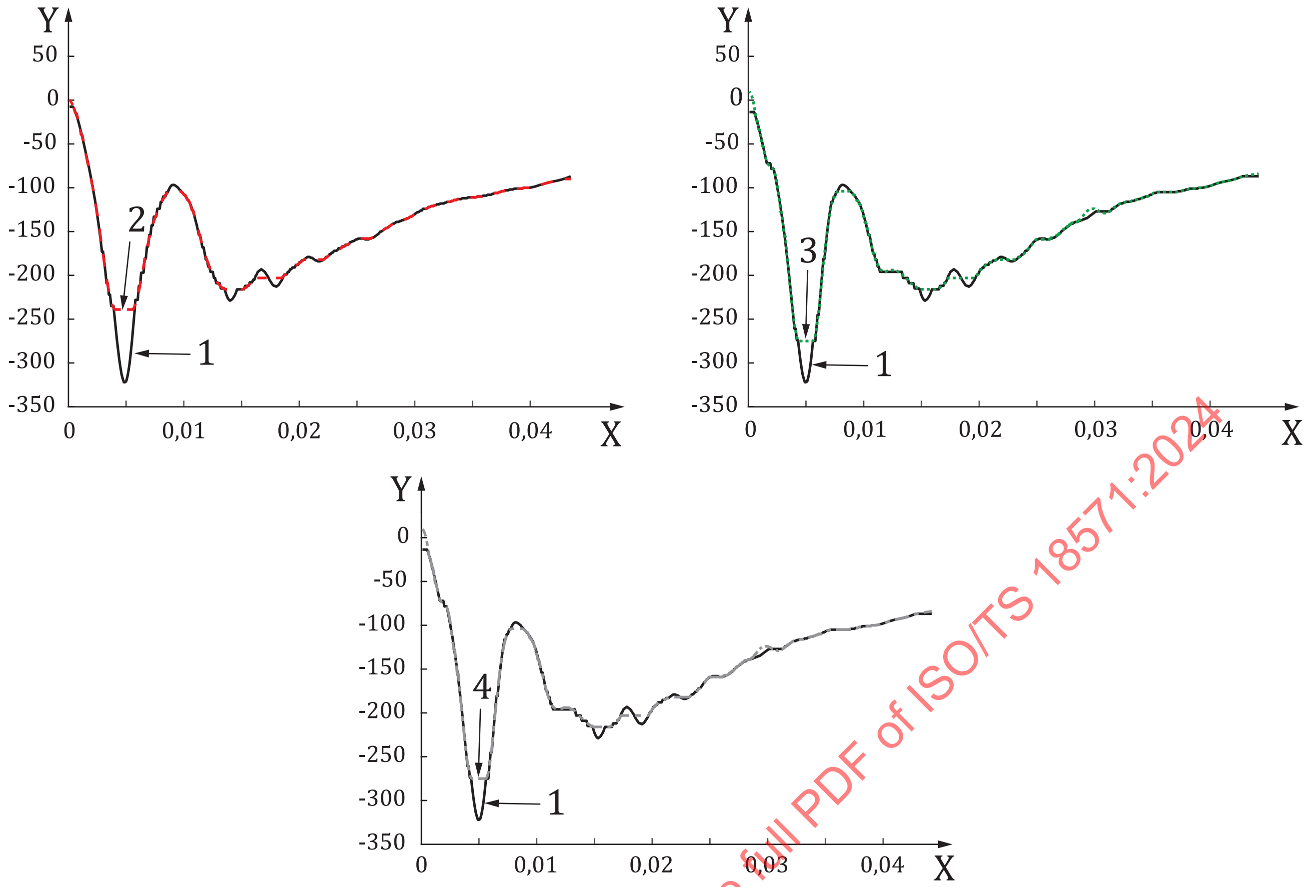
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.2.4 — Slope of time shifted curves



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

1 test warped

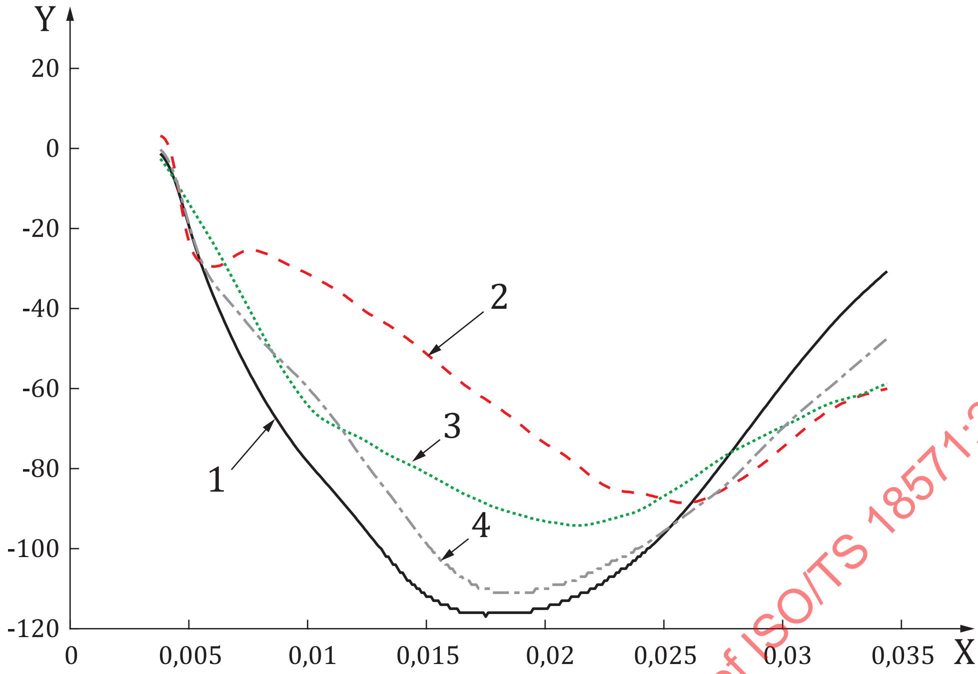
2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.2.5 — Warped time shifted curves

A.2.2 Acceleration 2



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

1 test

2 CAE1

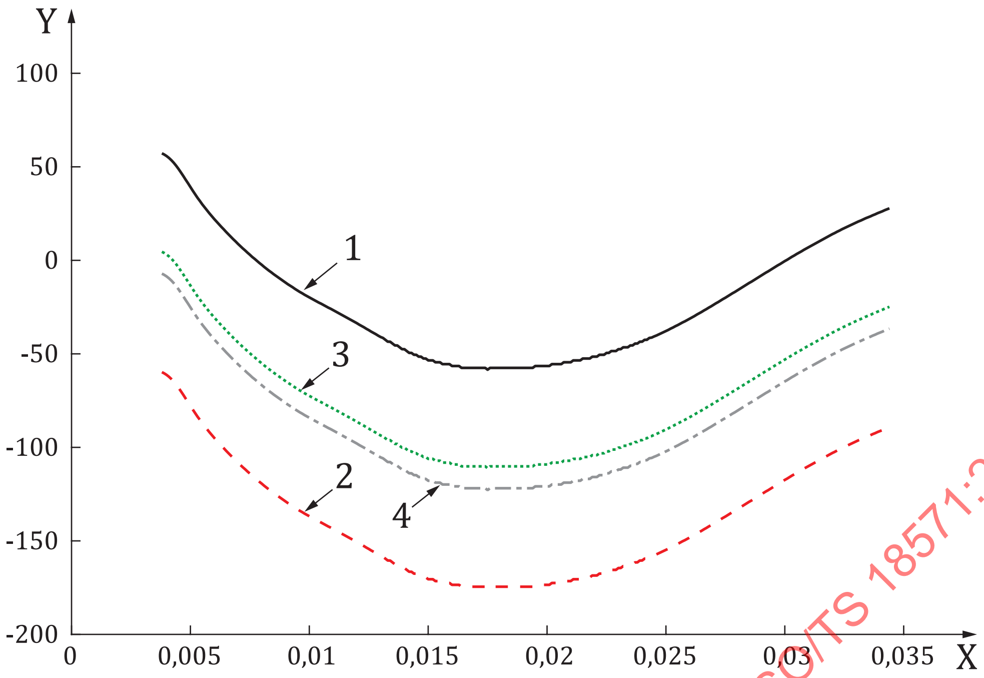
3 CAE2

4 CAE3

Figure A.2.6 — Original curves

Table A.2.2 — ISO rating results

	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Poor	Fair	Good
Overall rating R	0,437 9	0,699 3	0,854 2
Corridor score Z	0,405 9	0,642 3	0,845 2
Phase score E_P	0,006 5	0,625 4	0,772 0
Magnitude score E_M	0,647 1	0,821 9	0,965 9
Slope score E_S	0,724 1	0,764 8	0,842 7



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

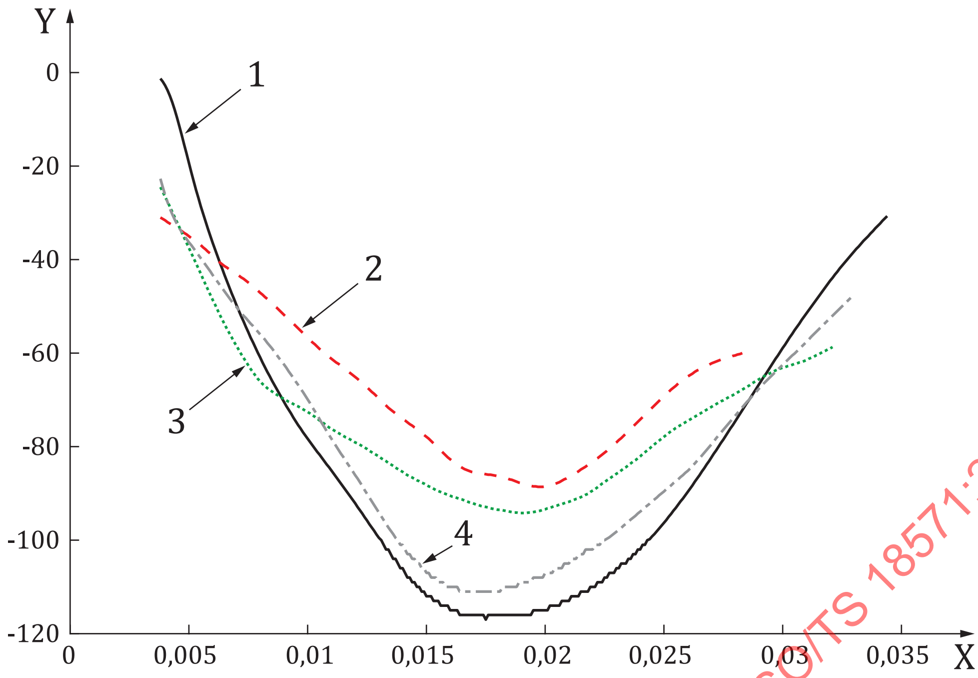
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.2.7 — Corridor curves



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

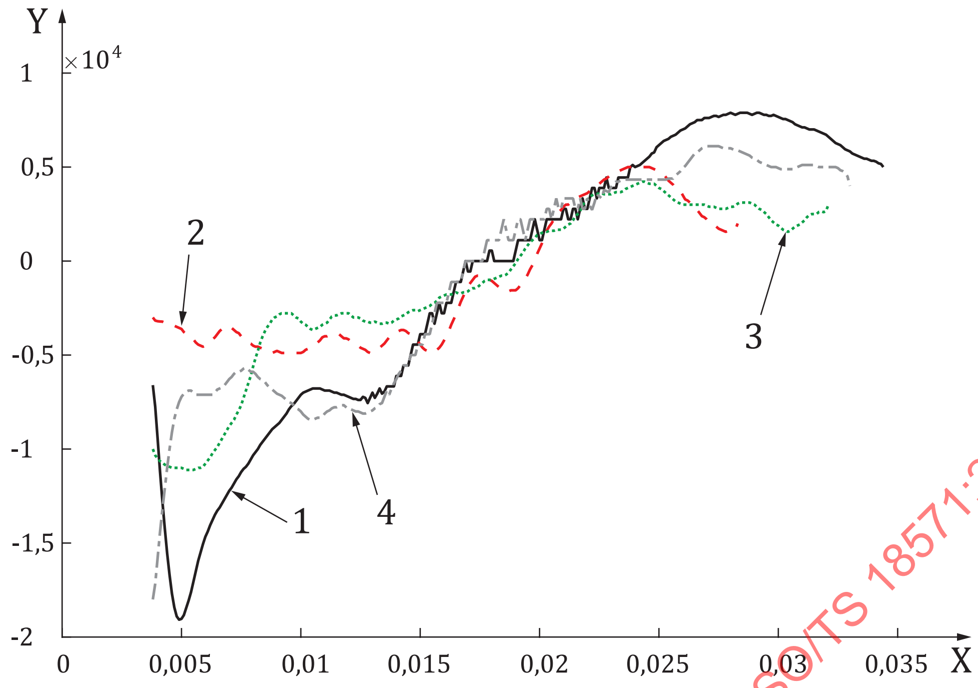
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.2.8 — Time shifted curves



Key

X t, time [s]

Y s, slope of acceleration curve[m/s^3]

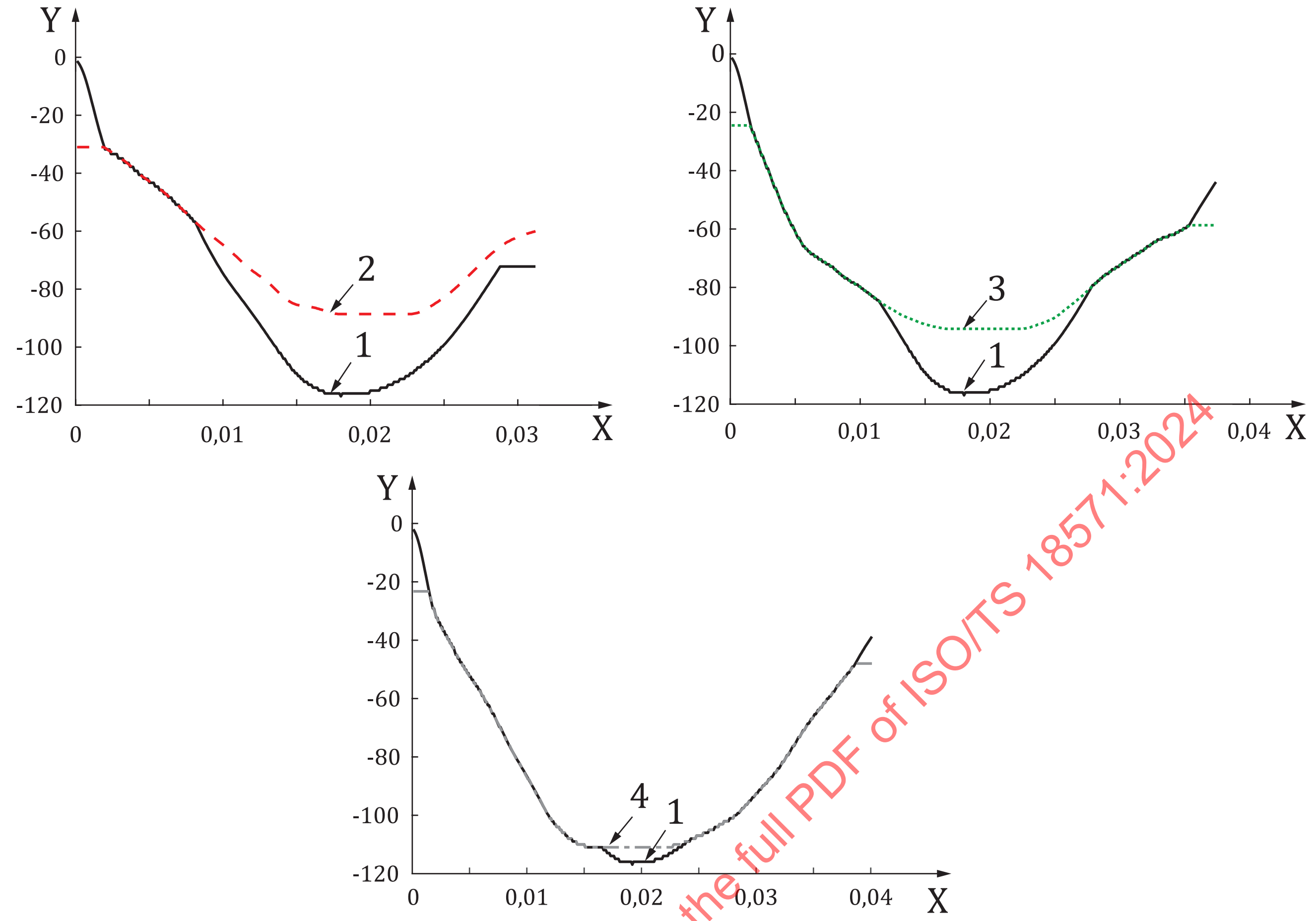
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.2.9 — Slope of time shifted curves



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

1 test warped

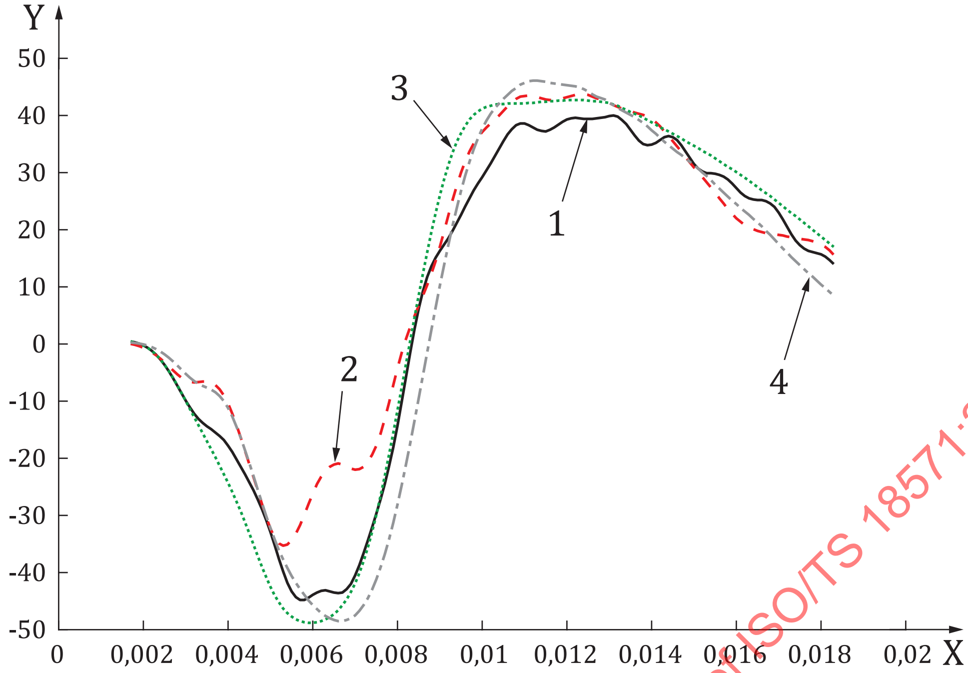
2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.2.10 — Warped time shifted curves

A.2.3 Acceleration 3



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

1 test

2 CAE1

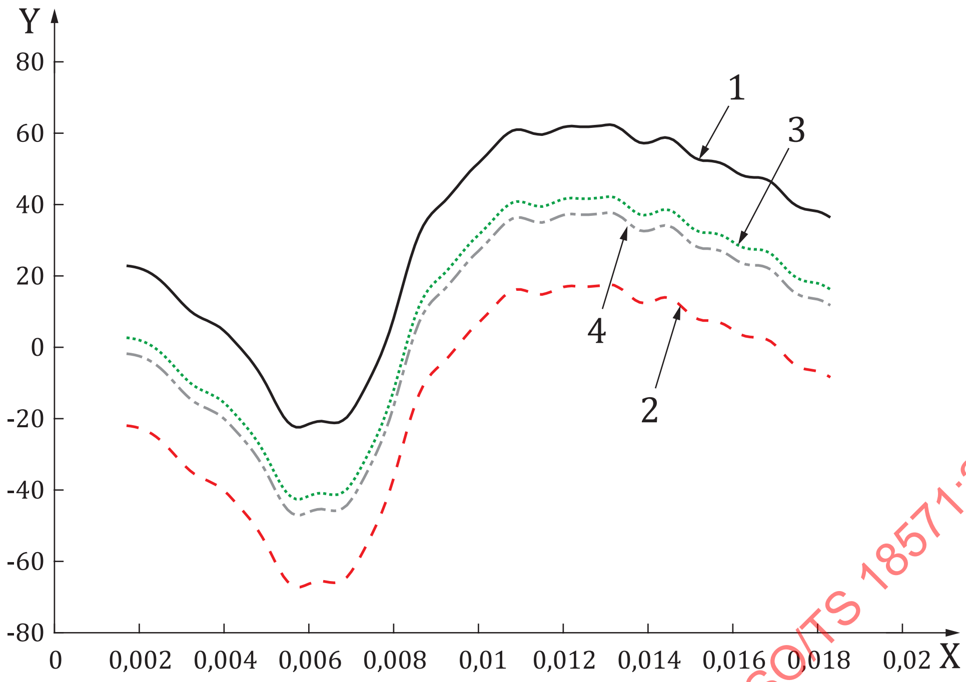
3 CAE2

4 CAE3

Figure A.2.11 — Original curves

Table A.2.3 — ISO rating results

	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Fair	Good	Good
Overall rating R	0,804 5	0,870 1	0,831 4
Corridor score Z	0,726 3	0,816 4	0,749 9
Phase score E_P	0,940 1	0,940 1	0,940 1
Magnitude score E_M	0,897 7	0,931 0	0,908 8
Slope score E_S	0,732 1	0,846 7	0,808 4



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

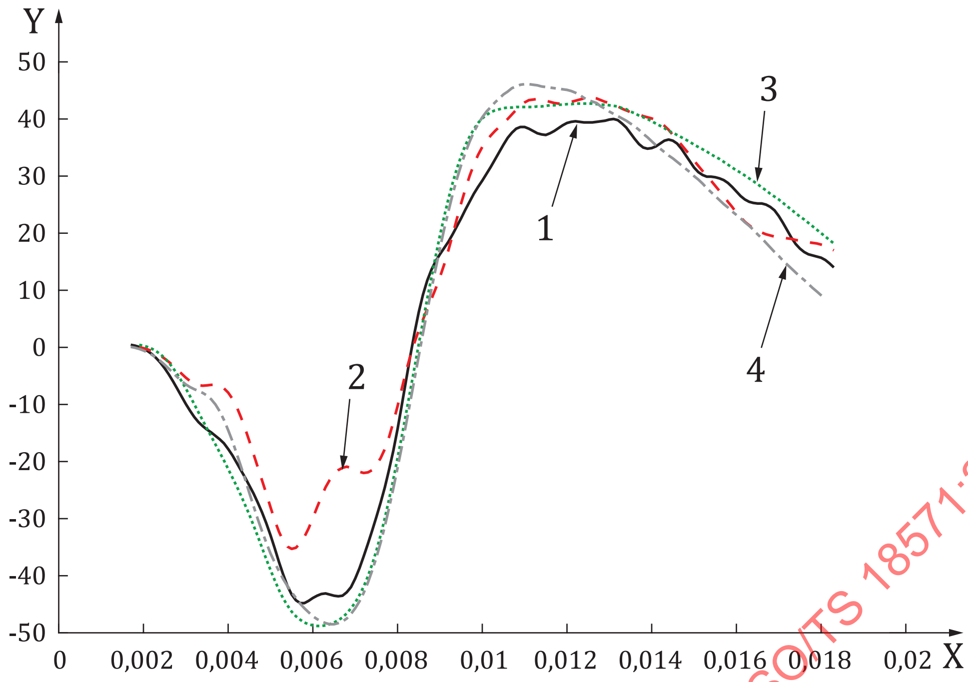
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.2.12 — Corridor curves



Key

X t, time [s]

Y a, acceleration [m/s^2]

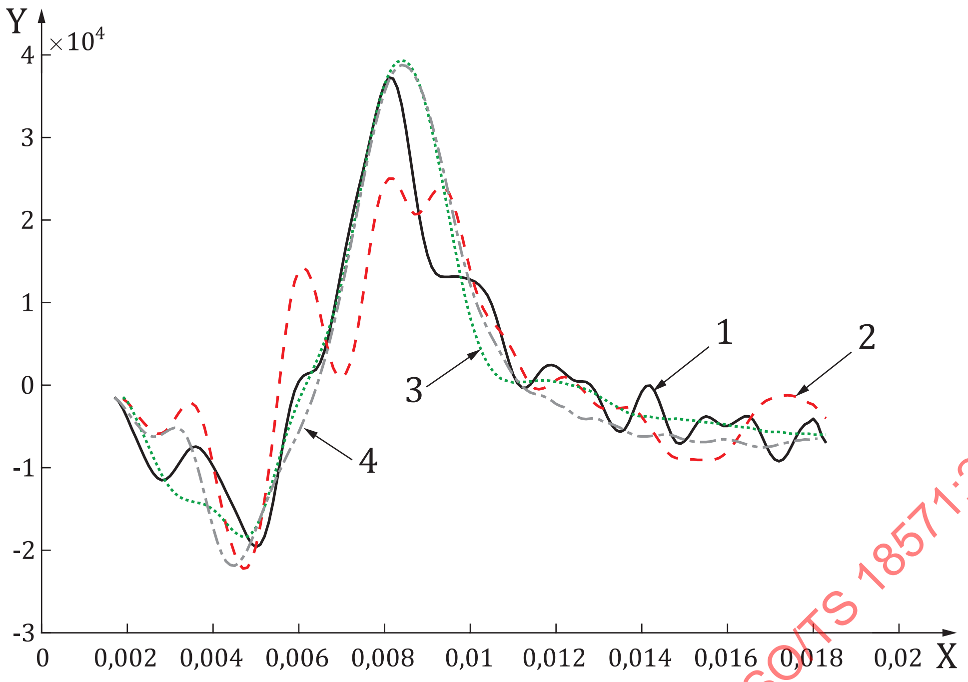
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.2.13 — Time shifted curves



Key

X *t*, time [s]

Y *s*, slope of acceleration curve[m/s^3]

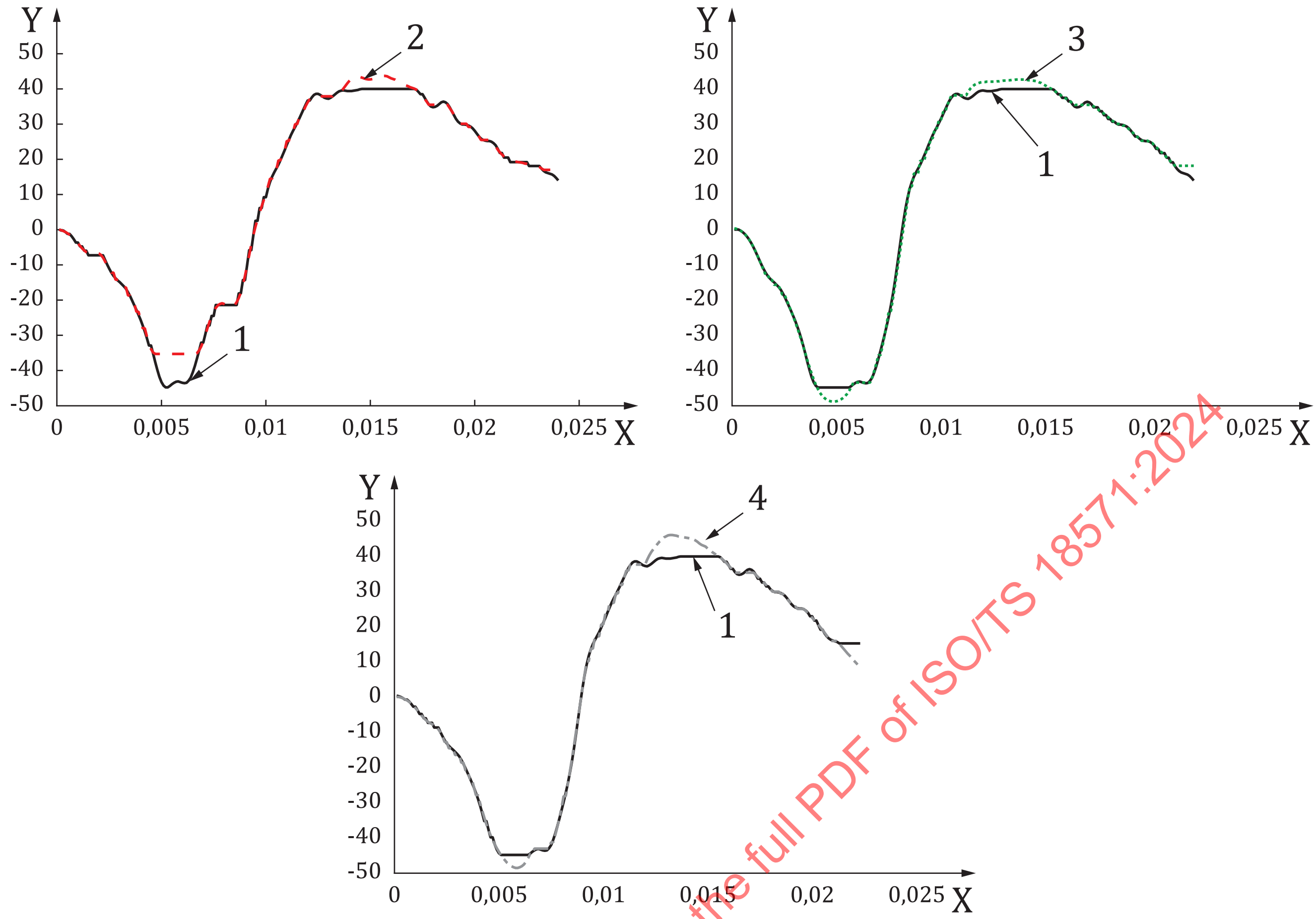
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.2.14 — Slope of time shifted curves



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

1 test warped

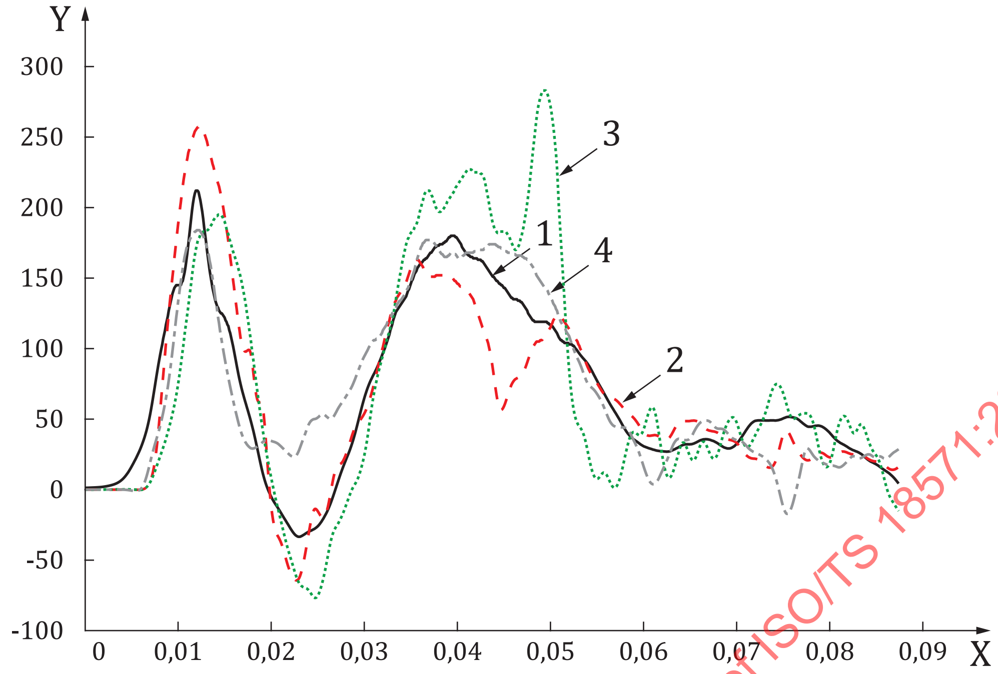
2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.2.15 — Warped time shifted curves

A.2.4 Acceleration 4



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

1 test

2 CAE1

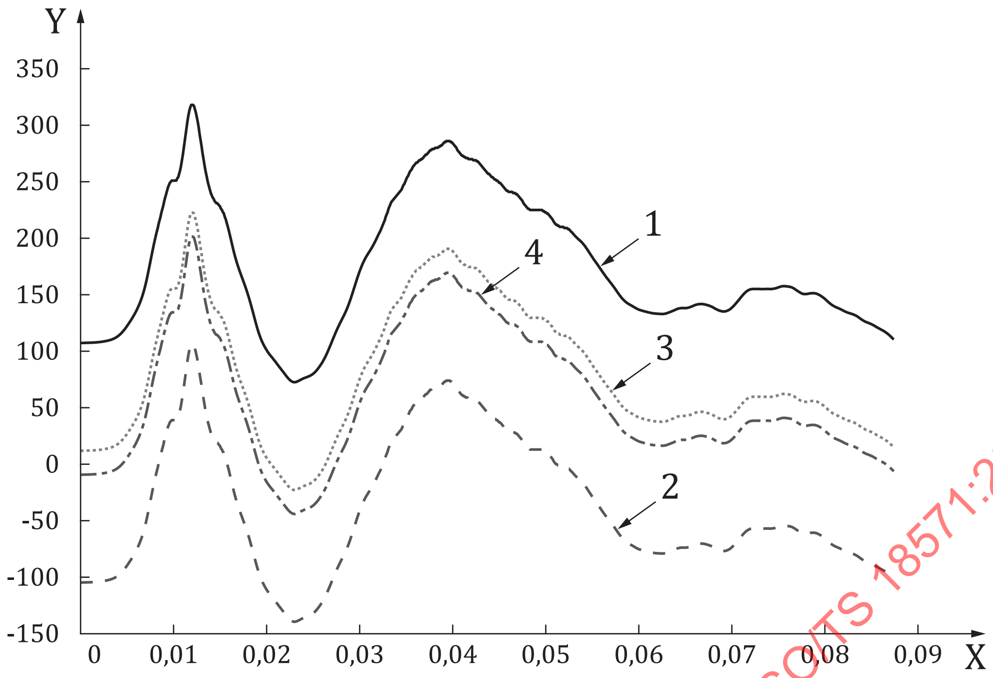
3 CAE2

4 CAE3

Figure A.2.16 — Original curves

Table A.2.4 — ISO rating results

	CAE1 (C_1)	CAE2 (C_2)	CAE3 (C_3)
Grade	Fair	Fair	Fair
Overall rating R	0,787 7	0,654 0	0,791 0
Corridor score Z	0,792 7	0,647 6	0,783 7
Phase score E_P	0,977 1	0,920 0	0,994 3
Magnitude score E_M	0,870 9	0,790 9	0,848 6
Slope score E_S	0,505 2	0,264 1	0,544 6



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

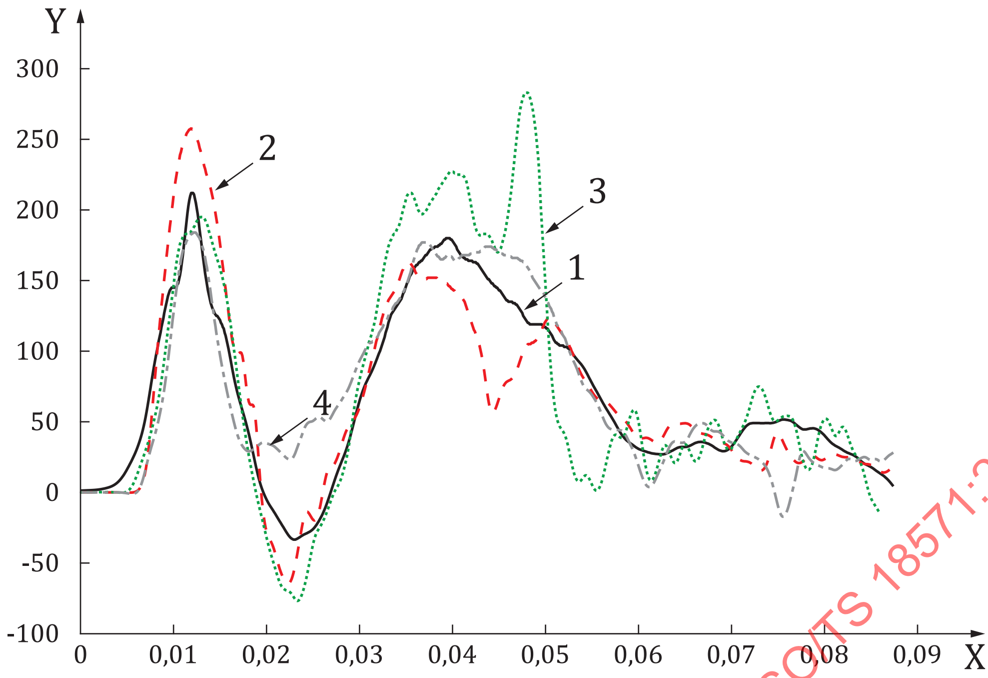
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.2.17 — Corridor curves



Key

X *t*, time [s]

Y *a*, acceleration [m/s^2]

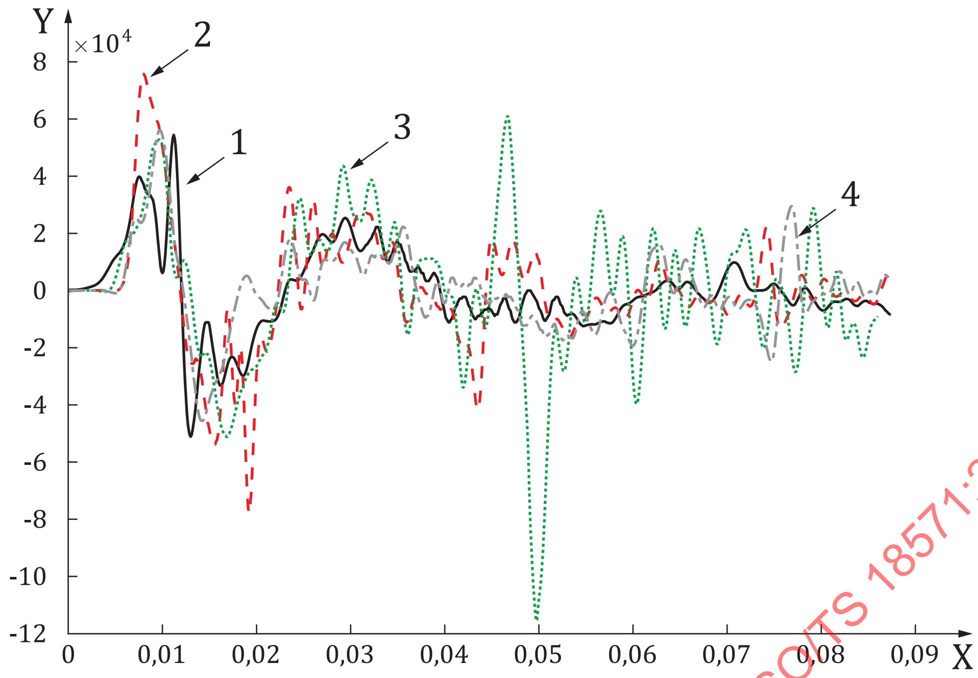
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.2.18 — Time shifted curves



Key

X *t*, time [s]

Y *s*, slope of acceleration curve [m/s^3]

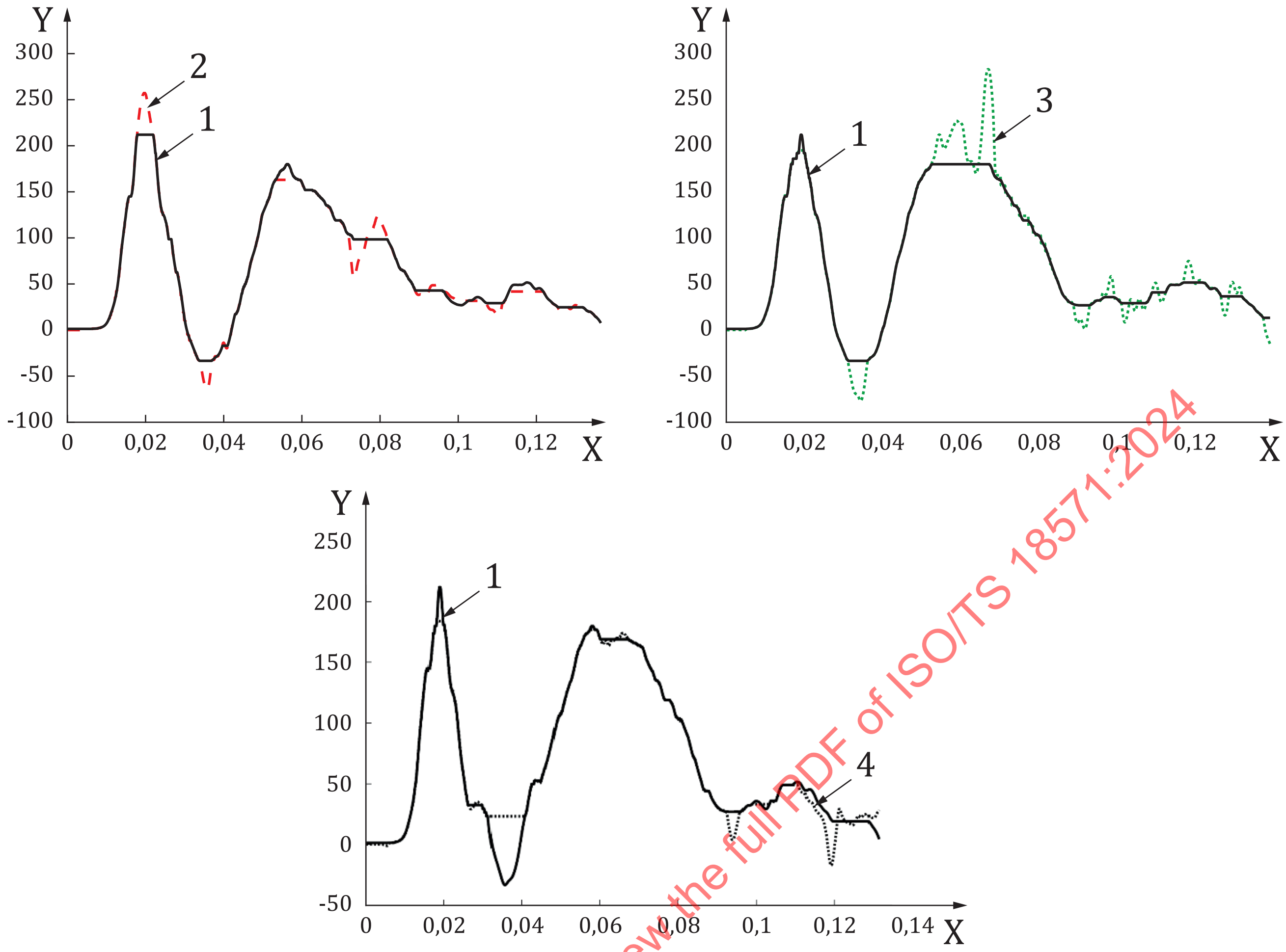
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.2.19 — Slope of time shifted curves



Key

X *t*, time [s]

Y *a*, acceleration curve [m/s^2]

1 test warped

2 CAE1 warped

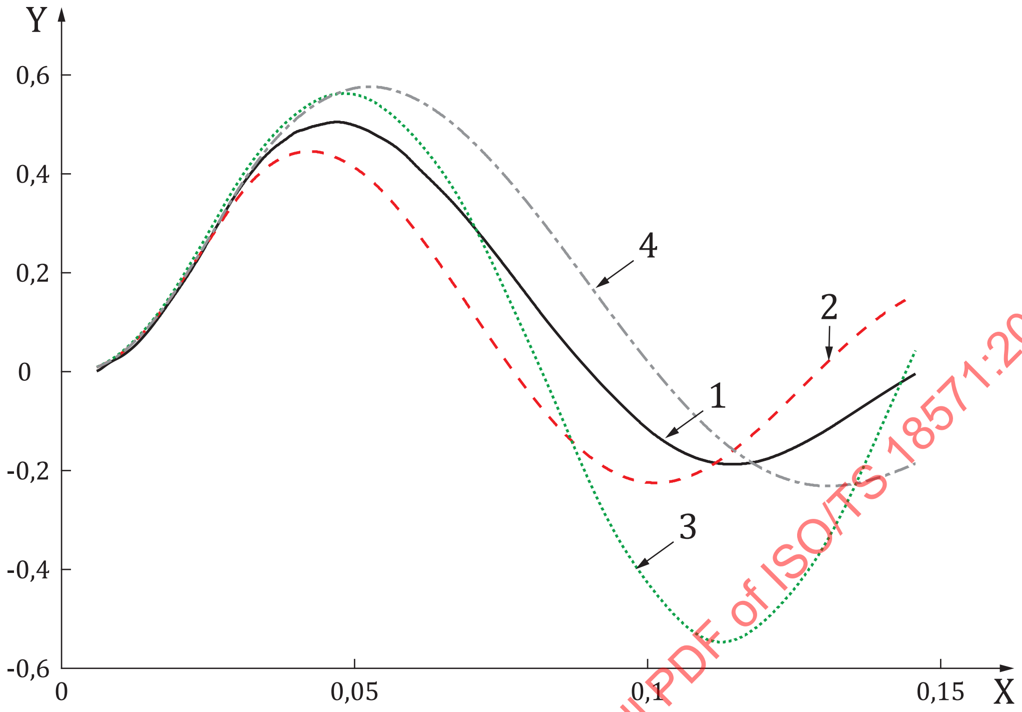
3 CAE2 warped

4 CAE3 warped

Figure A.2.20 — Warped time shifted curves

A.3 Angles

A.3.1 Angle 1



Key

X *t*, time [s]

Y α , angle [rad]

1 test

2 CAE1

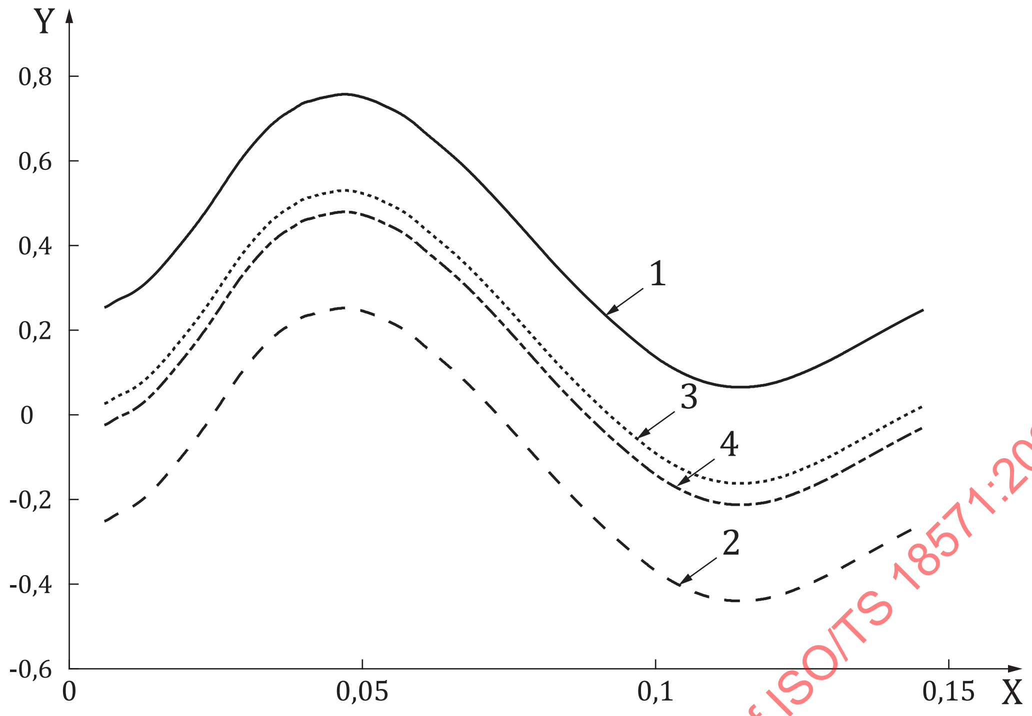
3 CAE2

4 CAE3

Figure A.3.1 — Original curves

Table A.3.1 — ISO rating results

	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Fair	Fair	Fair
Overall rating R	0,699 4	0,624 2	0,706 0
Corridor score Z	0,529 7	0,540 6	0,537 9
Phase score E_P	0,717 5	0,917 7	0,749 6
Magnitude score E_M	0,892 4	0,463 3	0,847 6
Slope score E_S	0,827 6	0,658 8	0,856 8



Key

X *t*, time [s]

Y *α* , angle [rad]

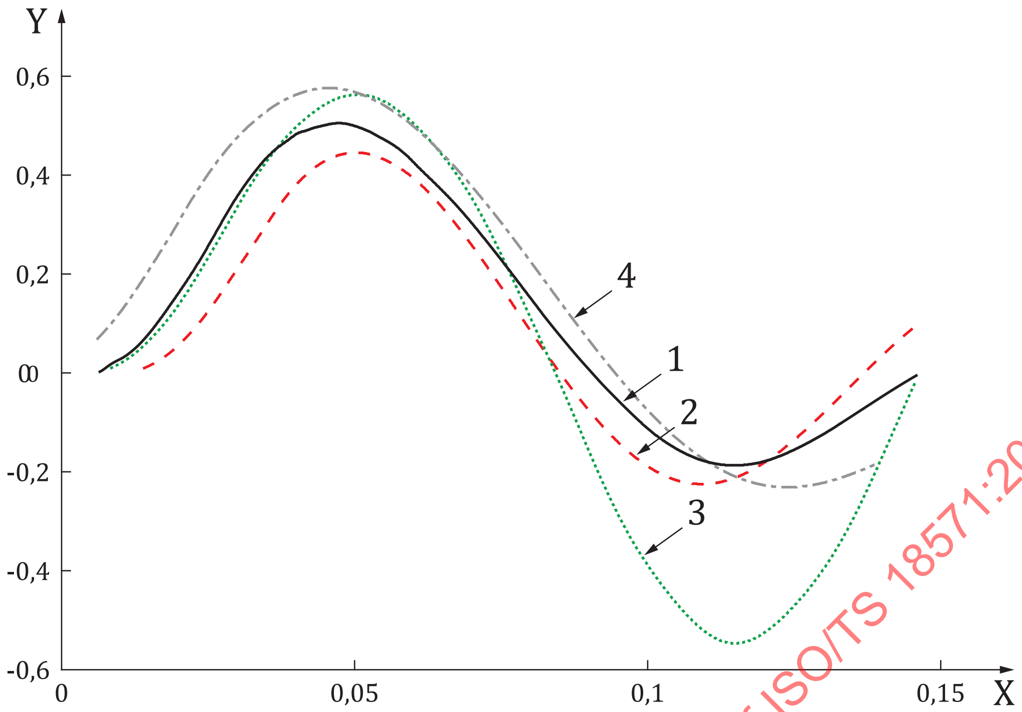
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.3.2 — Corridor curves



Key

X *t*, time [s]

Y α , angle [rad]

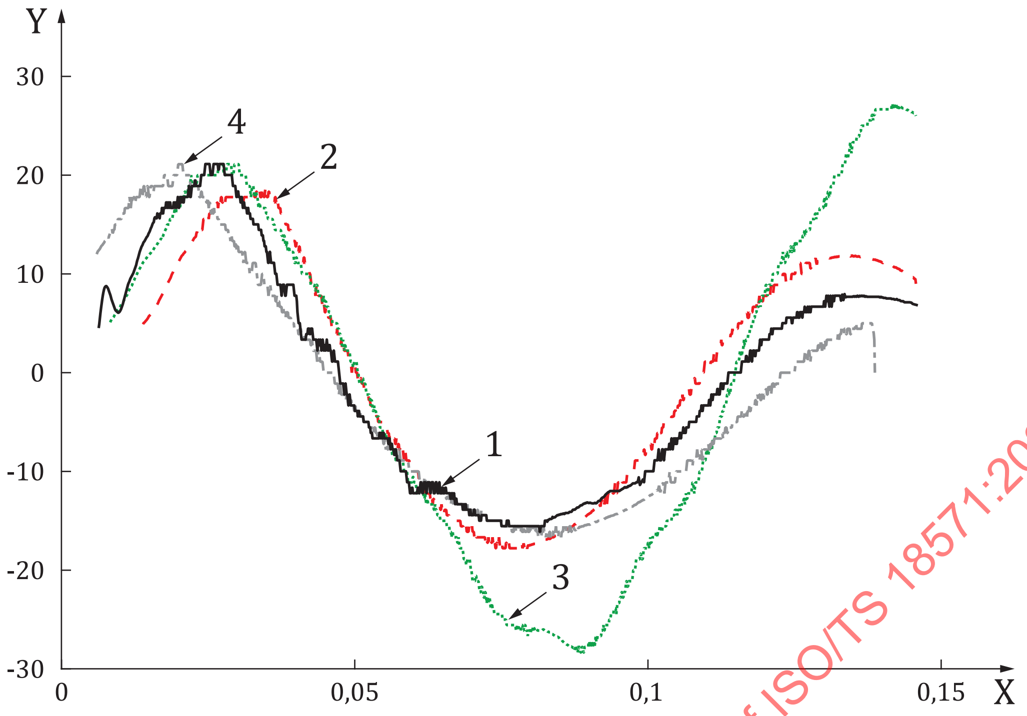
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.3.3 — Time shifted curves



Key

X *t*, time [s]

Y *s*, slope of angle curve [rad/s]

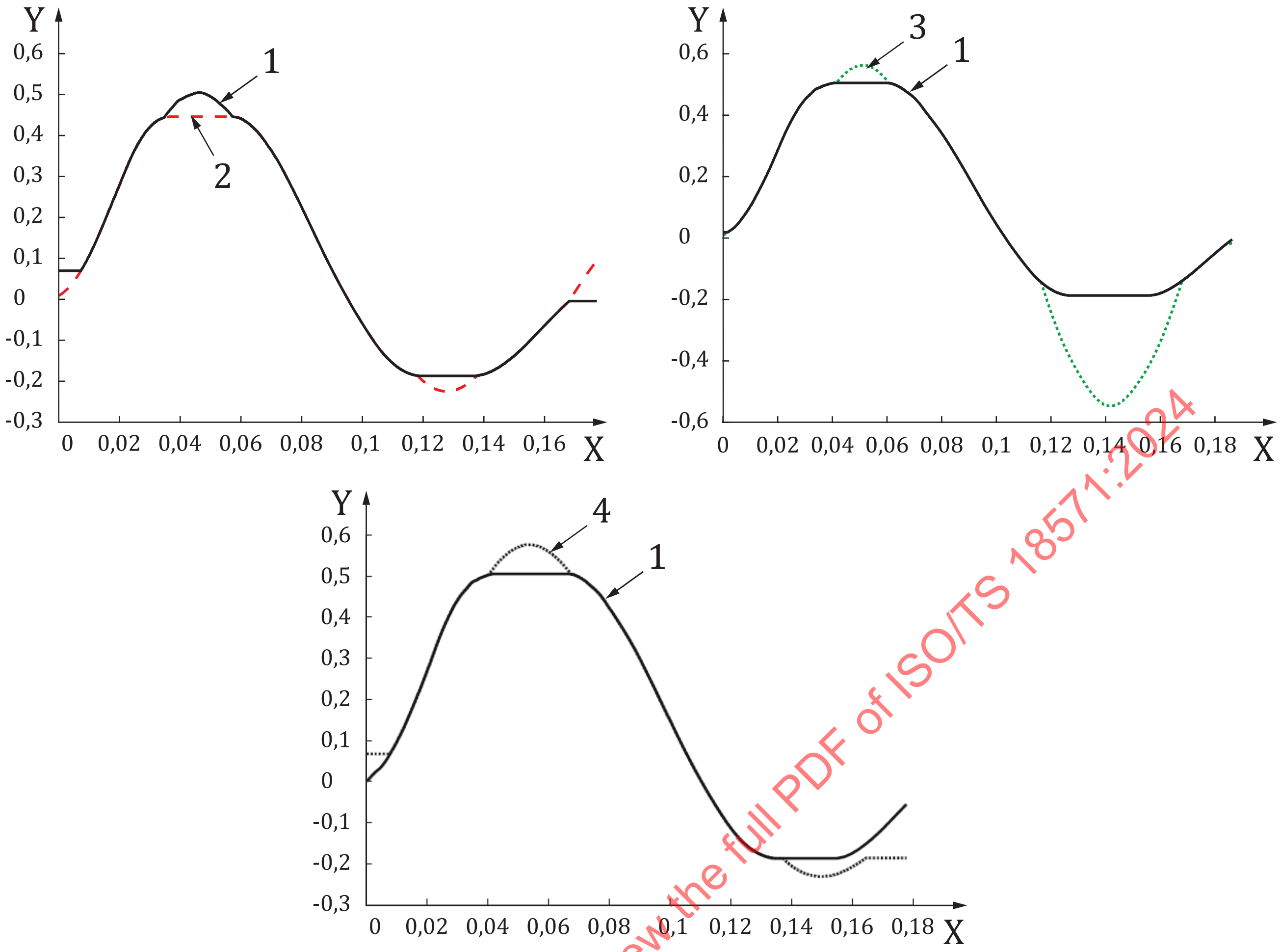
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.3.4 — Slope of time shifted curves

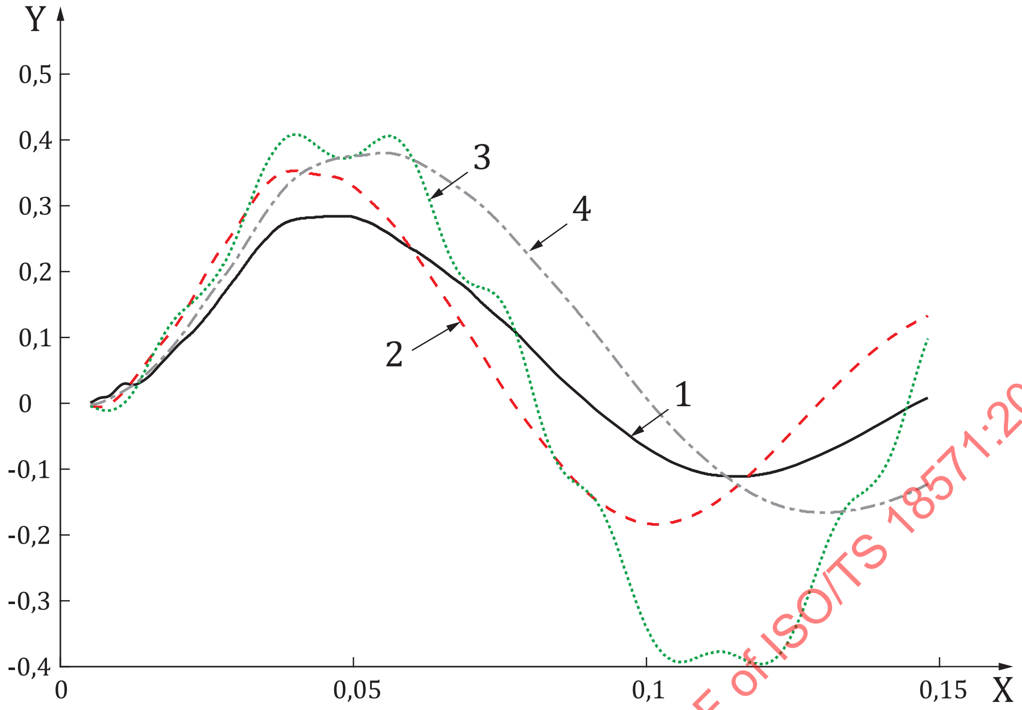


Key

X	*t*, time [s]
Y	α , angle [rad]
1	test warped
2	CAE1 warped
3	CAE2 warped
4	CAE3 warped

Figure A.3.5 — Warped time shifted curves

A.3.2 Angle 2



Key

X *t*, time [s]

Y *α* , angle [rad]

1 test

2 CAE1

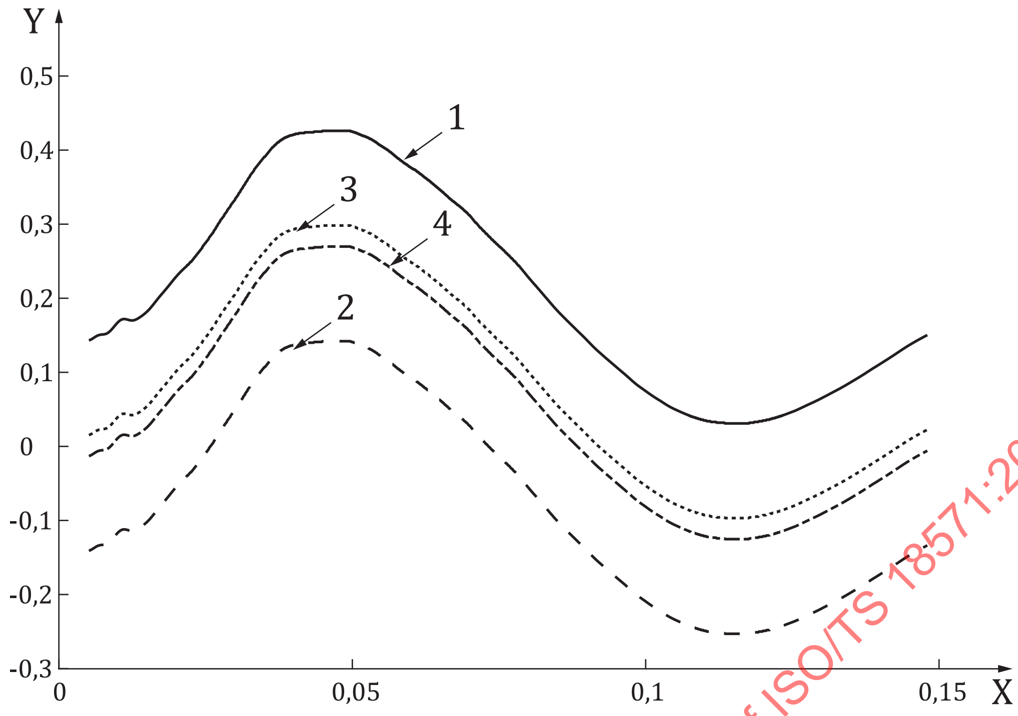
3 CAE2

4 CAE3

Figure A.3.6 — Original curves

Table A.3.2 — ISO rating results

	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Fair	Poor	Fair
Overall rating R	0,591 2	0,364 3	0,583 5
Corridor score Z	0,403 3	0,286 8	0,374 0
Phase score E_P	0,720 3	0,905 6	0,744 8
Magnitude score E_M	0,759 9	0,098 0	0,642 6
Slope score E_S	0,669 4	0,244 1	0,781 9



Key

X *t*, time [s]

Y α , angle [rad]

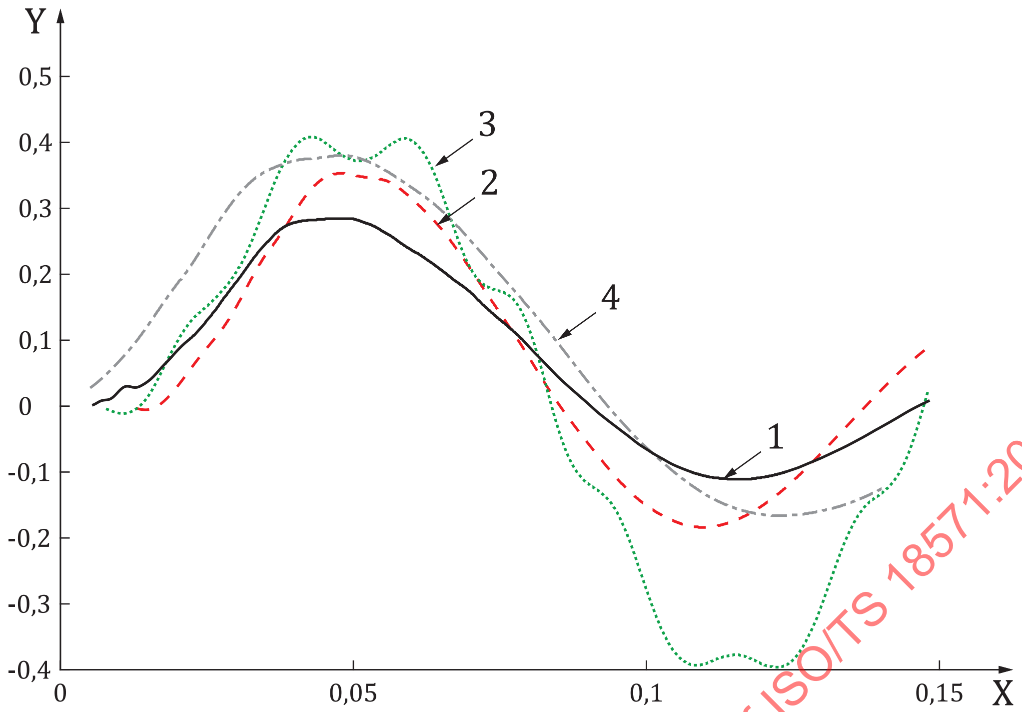
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.3.7 — Corridor curves



Key

X *t*, time [s]

Y α , angle [rad]

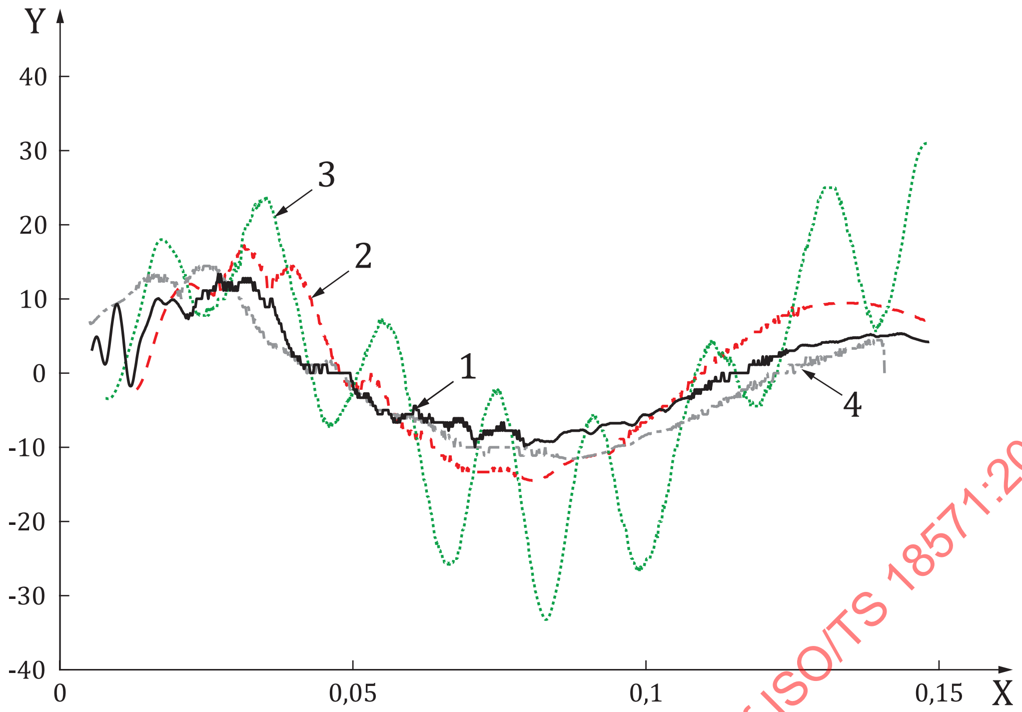
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.3.8 — Time shifted curves



Key

X *t*, time [s]

Y *s* , slope of angle curve [rad/s]

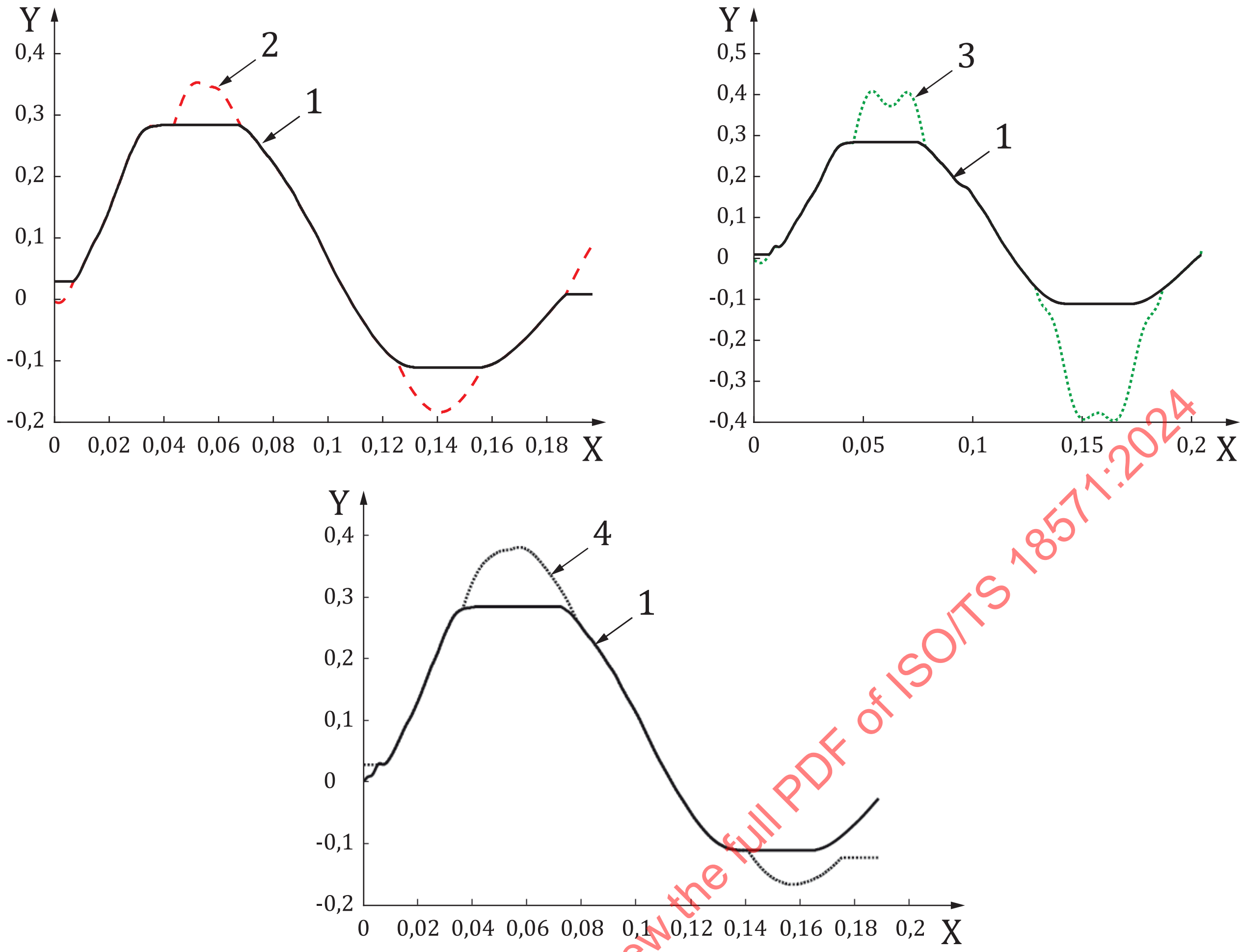
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.3.9 — Slope of time shifted curves



Key

X *t*, time [s]

Y α , angle [rad]

1 test warped

2 CAE1 warped

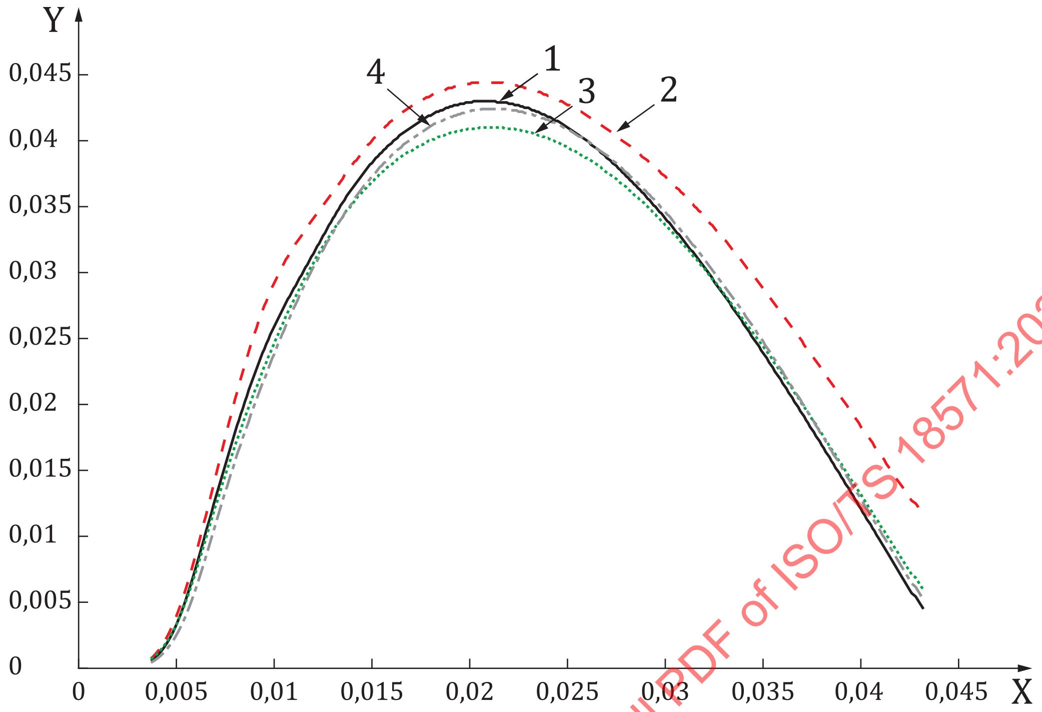
3 CAE2 warped

4 CAE3 warped

Figure A.3.10 — Warped time shifted curves

A.4 Displacements

A.4.1 Displacement 1



Key

X t, time [s]

Y s , displacement [m]

1 test

2 CAE1

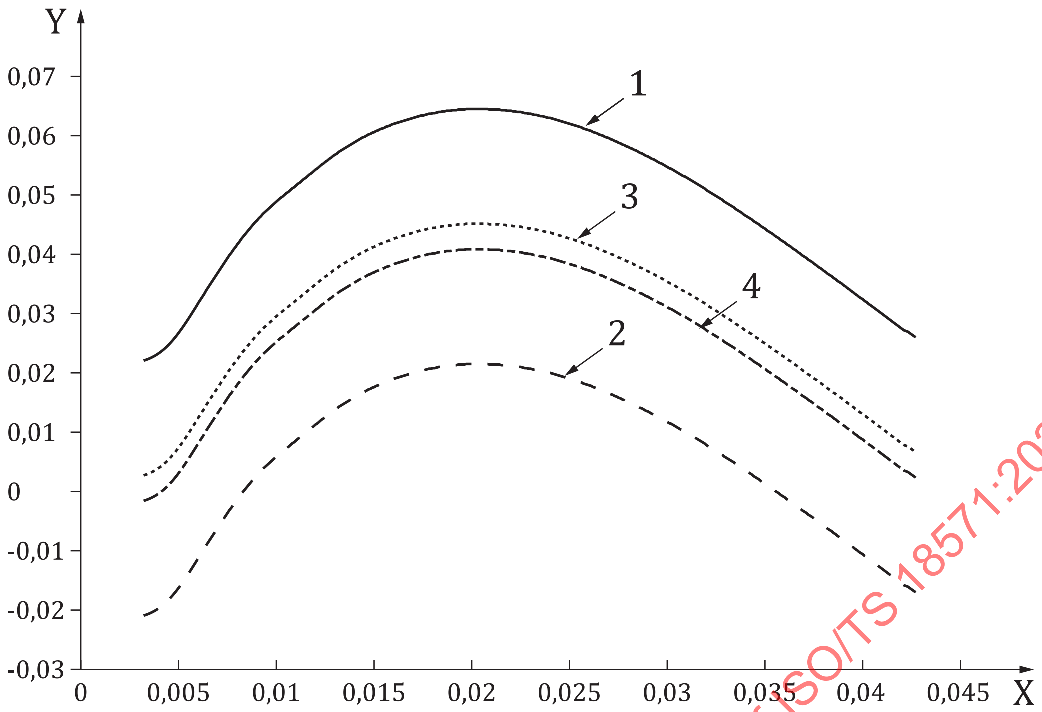
3 CAE2

4 CAE3

Figure A.4.1 — Original curves

Table A.4.1 — ISO rating results

	CAE1 (C_1)	CAE2 (C_2)	CAE3 (C_3)
Grade	Good	Excellent	Excellent
Overall rating R	0,921 4	0,982 5	0,983 4
Corridor score Z	0,887 8	1,000 0	0,999 4
Phase score E_P	0,936 9	0,974 7	0,949 5
Magnitude score E_M	0,976 5	0,981 4	0,994 8
Slope score E_S	0,918 2	0,956 3	0,974 1



Key

X *t*, time [s]

Y *s* , displacement [m]

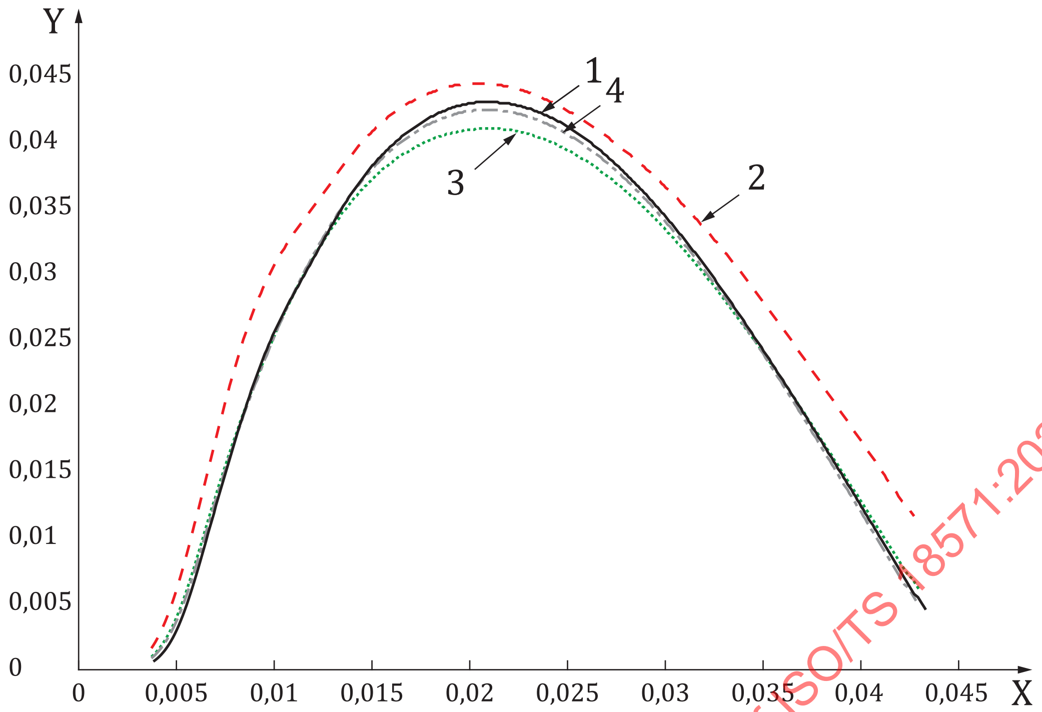
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.4.2 — Corridor curves



Key

X *t*, time [s]

Y *s*, displacement [m]

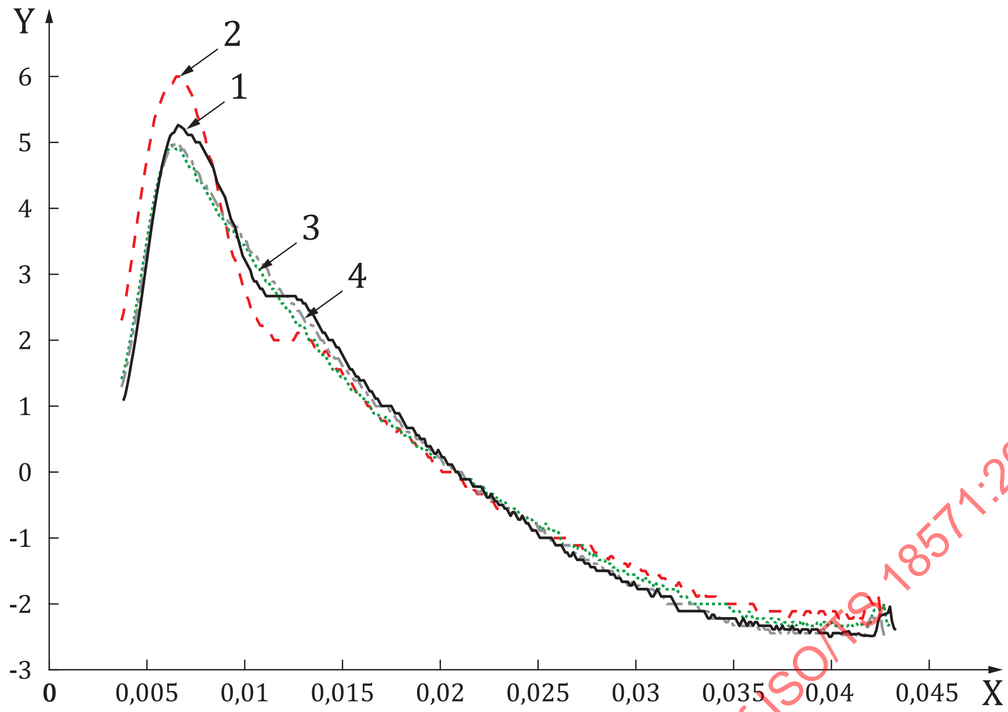
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.4.3 — Time shifted curves



Key

X *t*, time [s]

Y *s*, slope of displacement curve [m/s]

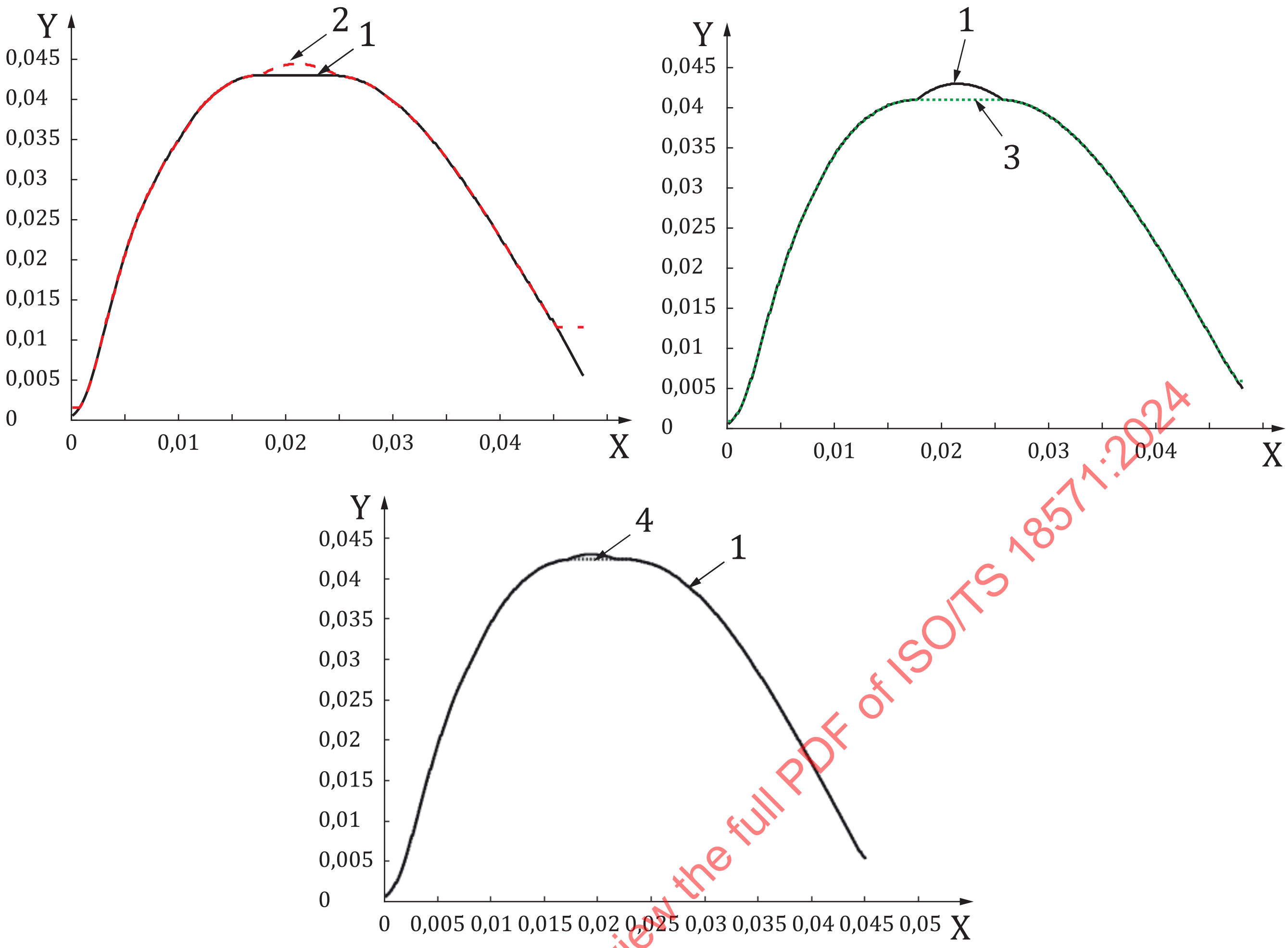
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.4.4 — Slope of time shifted curves



Key

X *t*, time [s]

Y *s* , displacement [m]

1 test warped

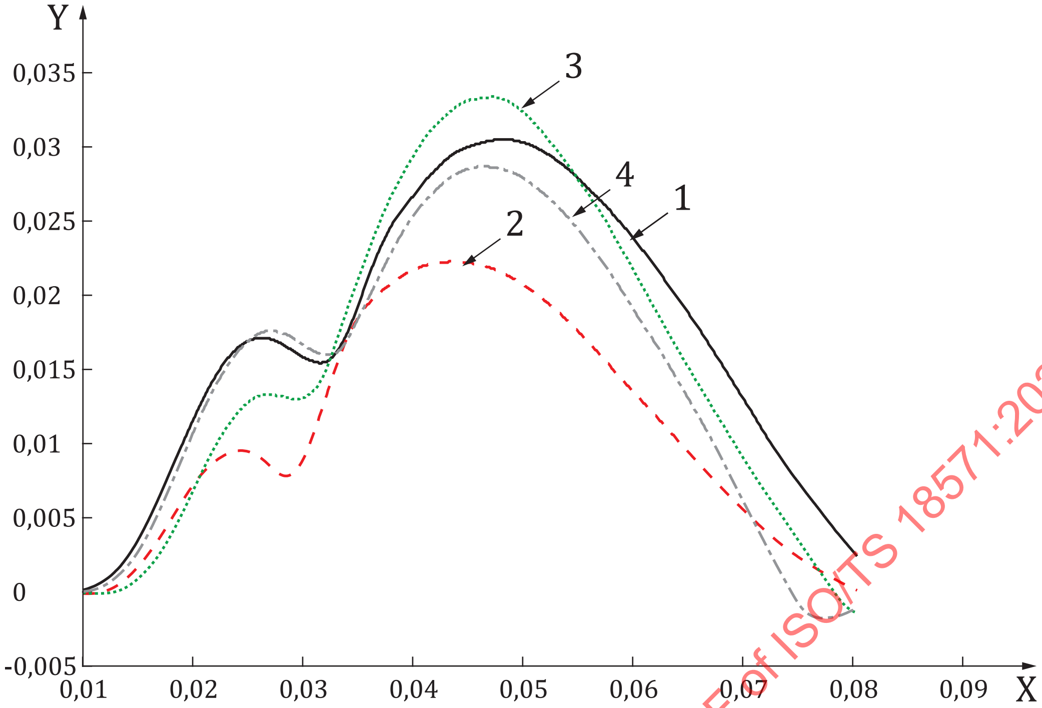
2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.4.5 — Warped time shifted curves

A.4.2 Displacement 2



Key

X   *t*, time [s]

Y   *s*, displacement [m]

1   test

2   CAE1

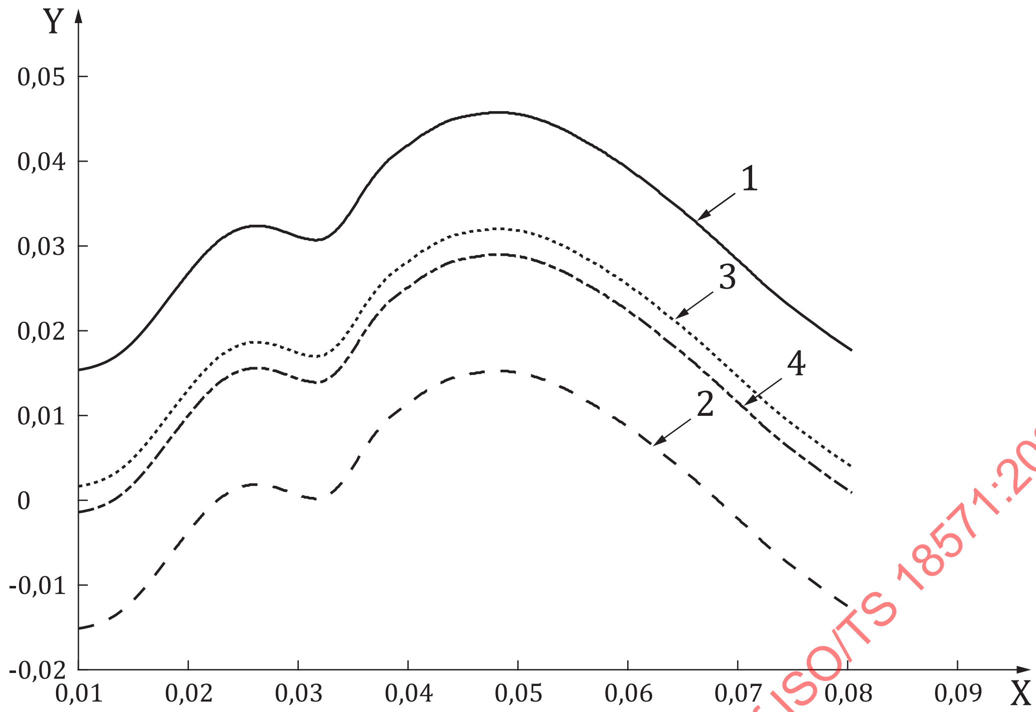
3   CAE2

4   CAE3

Figure A.4.6 — Original curves

Table A.4.2 — ISO rating results

	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Fair	Good	Good
Overall rating R	0,651 8	0,863 2	0,836 8
Corridor score Z	0,470 2	0,806 9	0,791 6
Phase score E_P	0,808 5	0,936 2	0,858 2
Magnitude score E_M	0,679 6	0,942 2	0,955 3
Slope score E_S	0,830 3	0,823 6	0,787 5



Key

X *t*, time [s]

Y *s* , displacement [m]

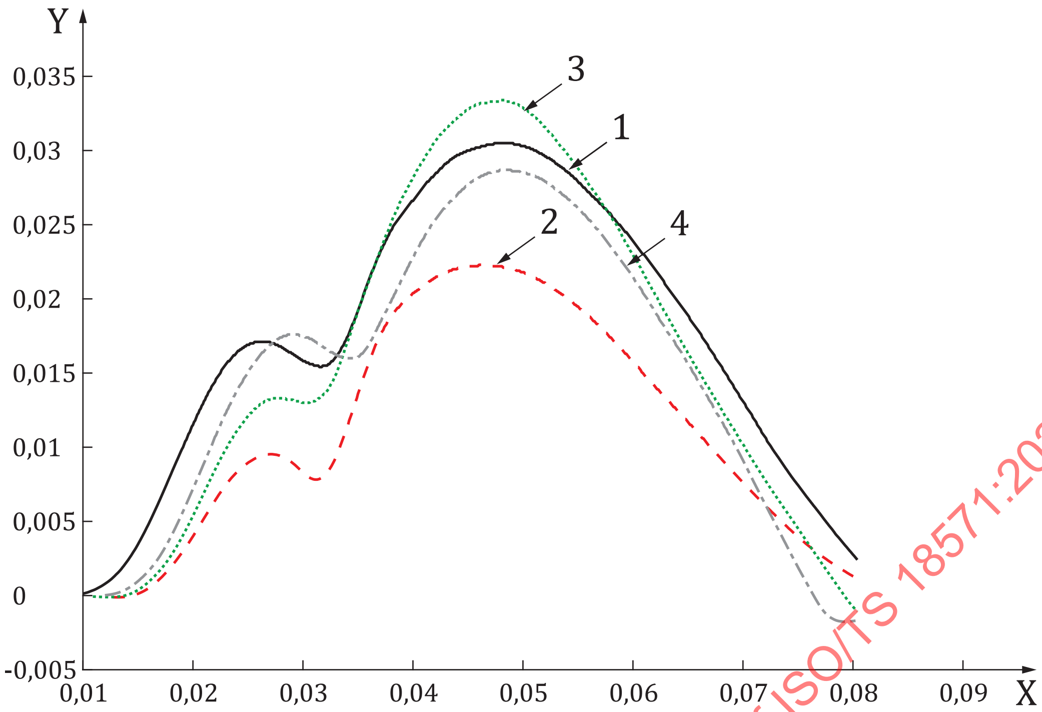
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.4.7 — Time shifted curves



Key

X *t*, time [s]

Y *s* , displacement [m]

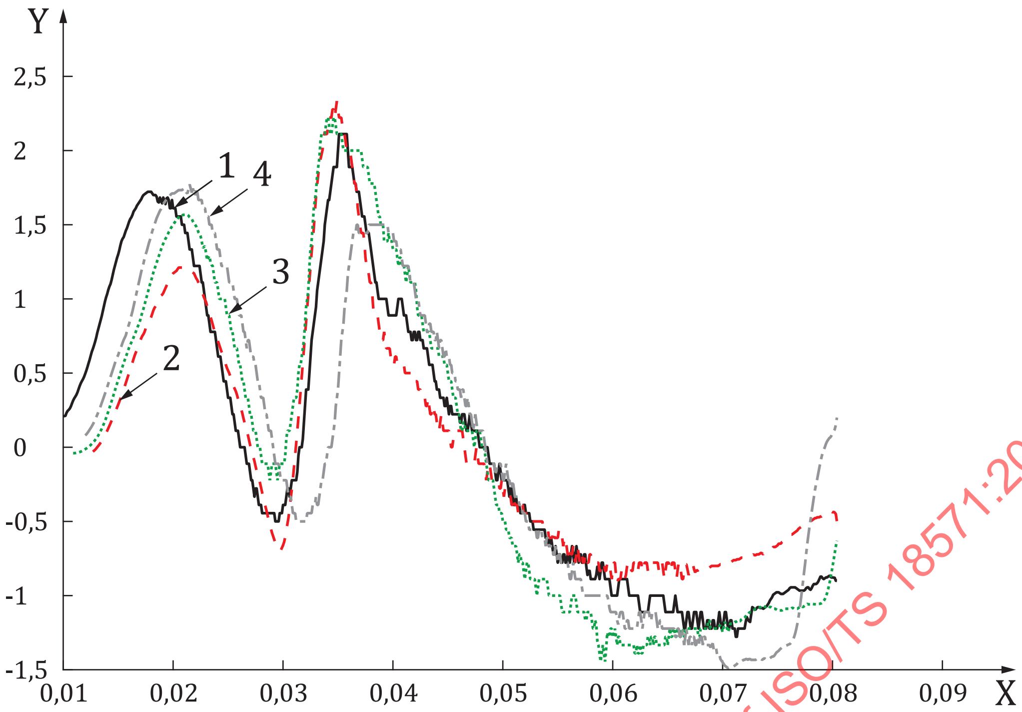
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.4.8 — Time shifted curves



Key

X *t*, time [s]

Y *s* , slope of displacement curve [m/s]

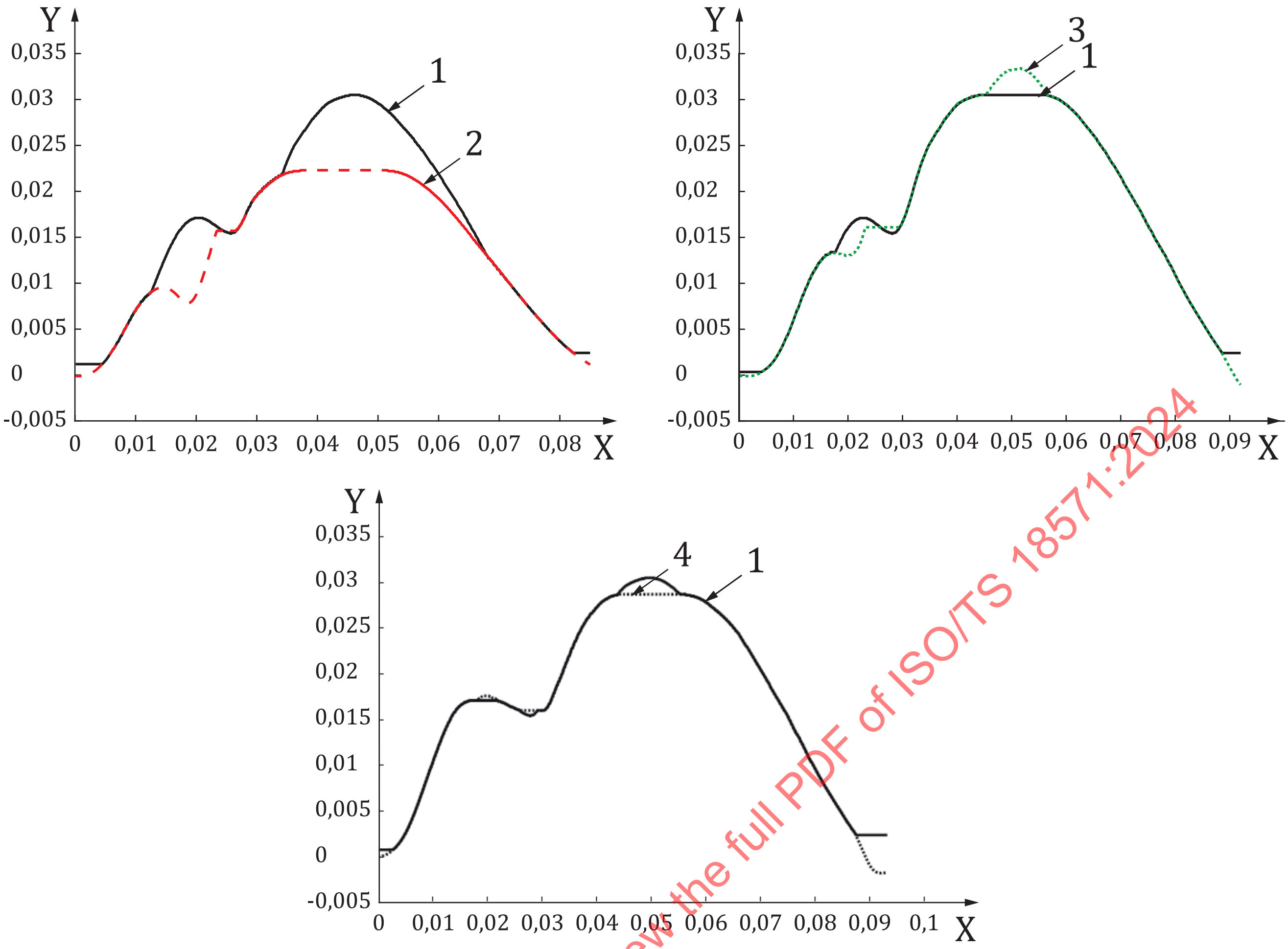
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.4.9 — Slope of time shifted curves



Key

X *t*, time [s]

Y *s* , displacement [m]

1 test warped

2 CAE1 warped

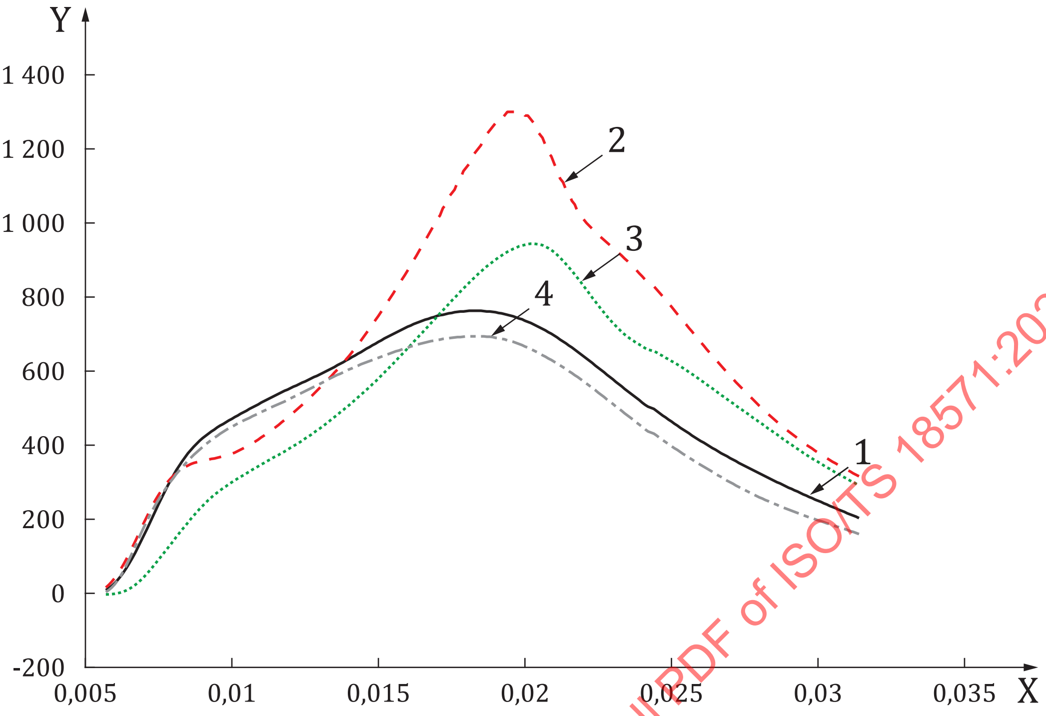
3 CAE2 warped

4 CAE3 warped

Figure A.4.10 — Warped time shifted curves

A.5 Forces

A.5.1 Force 1



Key

X *t*, time [s]

Y *f* , force [N]

1 test

2 CAE1

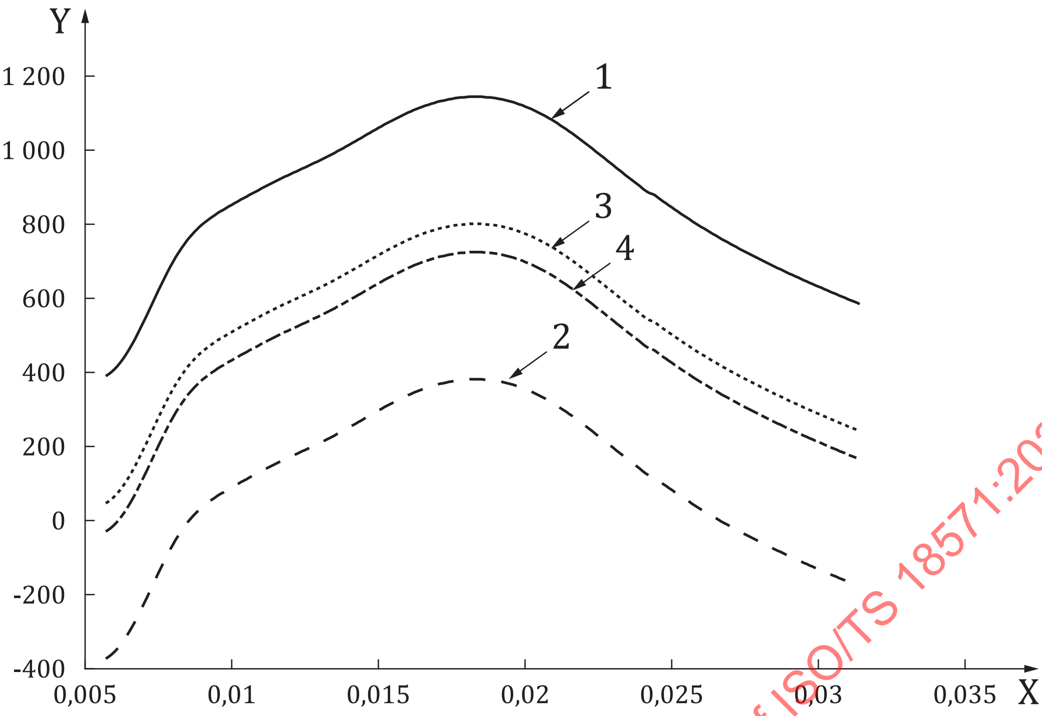
3 CAE2

4 CAE3

Figure A.5.1 — Original curves

Table A.5.1 — ISO rating results

	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Poor	Fair	Good
Overall rating *R*	0,536 4	0,655 6	0,929 7
Corridor score *Z*	0,450 1	0,526 7	0,911 2
Phase score E_P	0,689 9	0,593 0	0,922 5
Magnitude score E_M	0,617 7	0,911 1	0,957 2
Slope score E_S	0,473 9	0,720 6	0,946 5



Key

X *t*, time [s]

Y *f* , force [N]

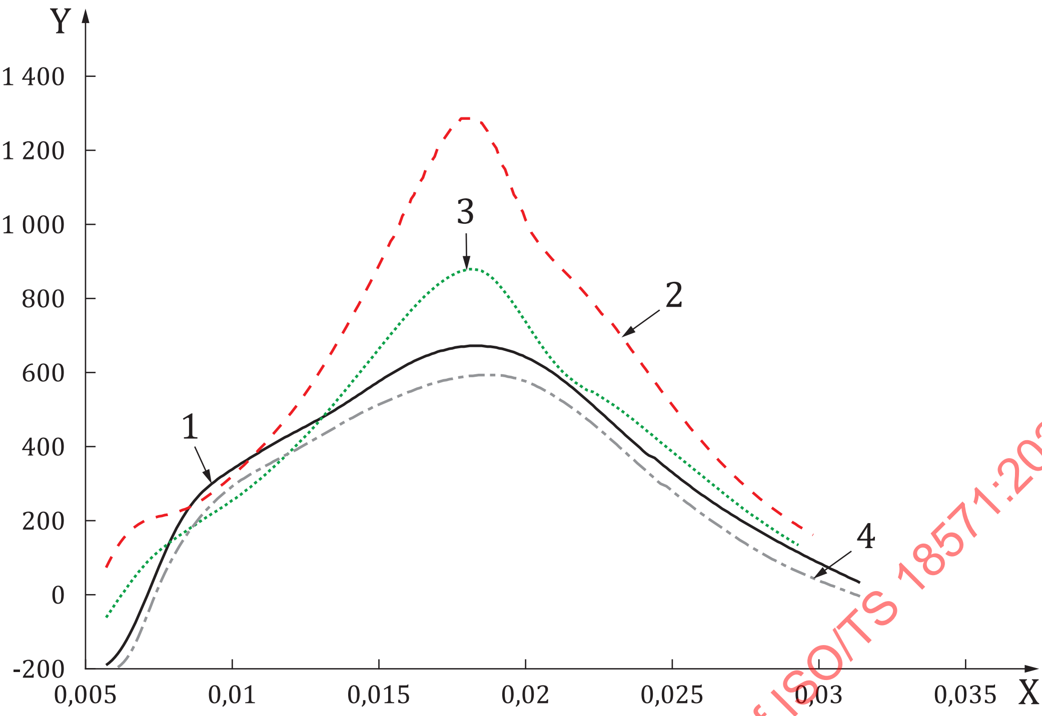
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.5.2 — Corridor curves



Key

X *t*, time [s]

Y *f* , force [N]

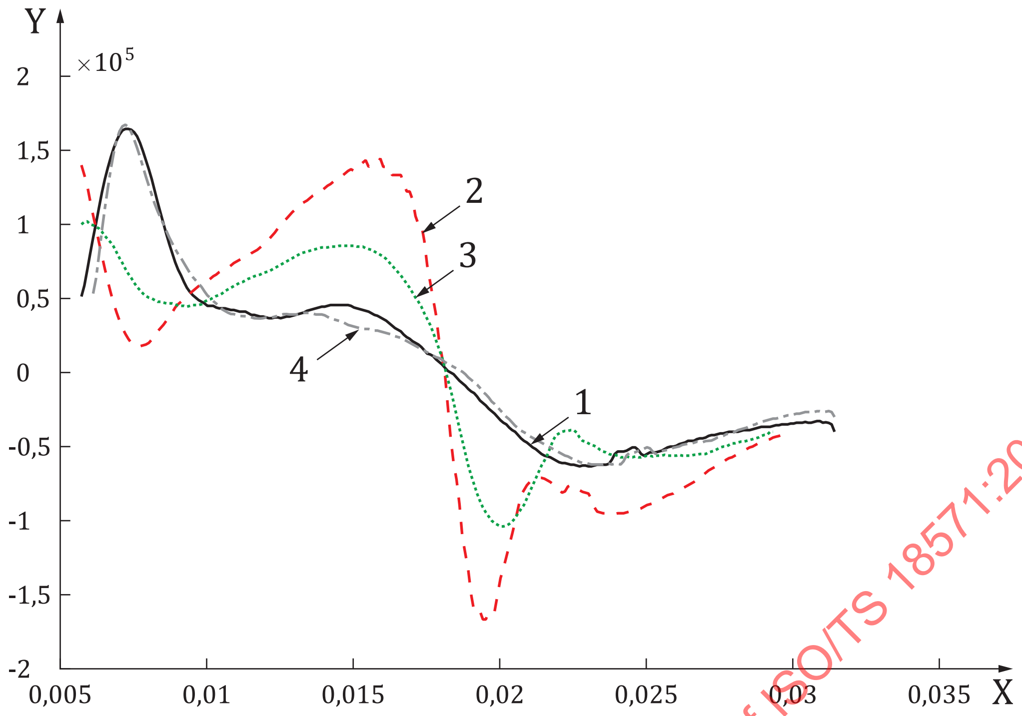
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.5.3 — Time shifted curves



Key

X *t*, time [s]

Y ω , slope of force curve [N/s]

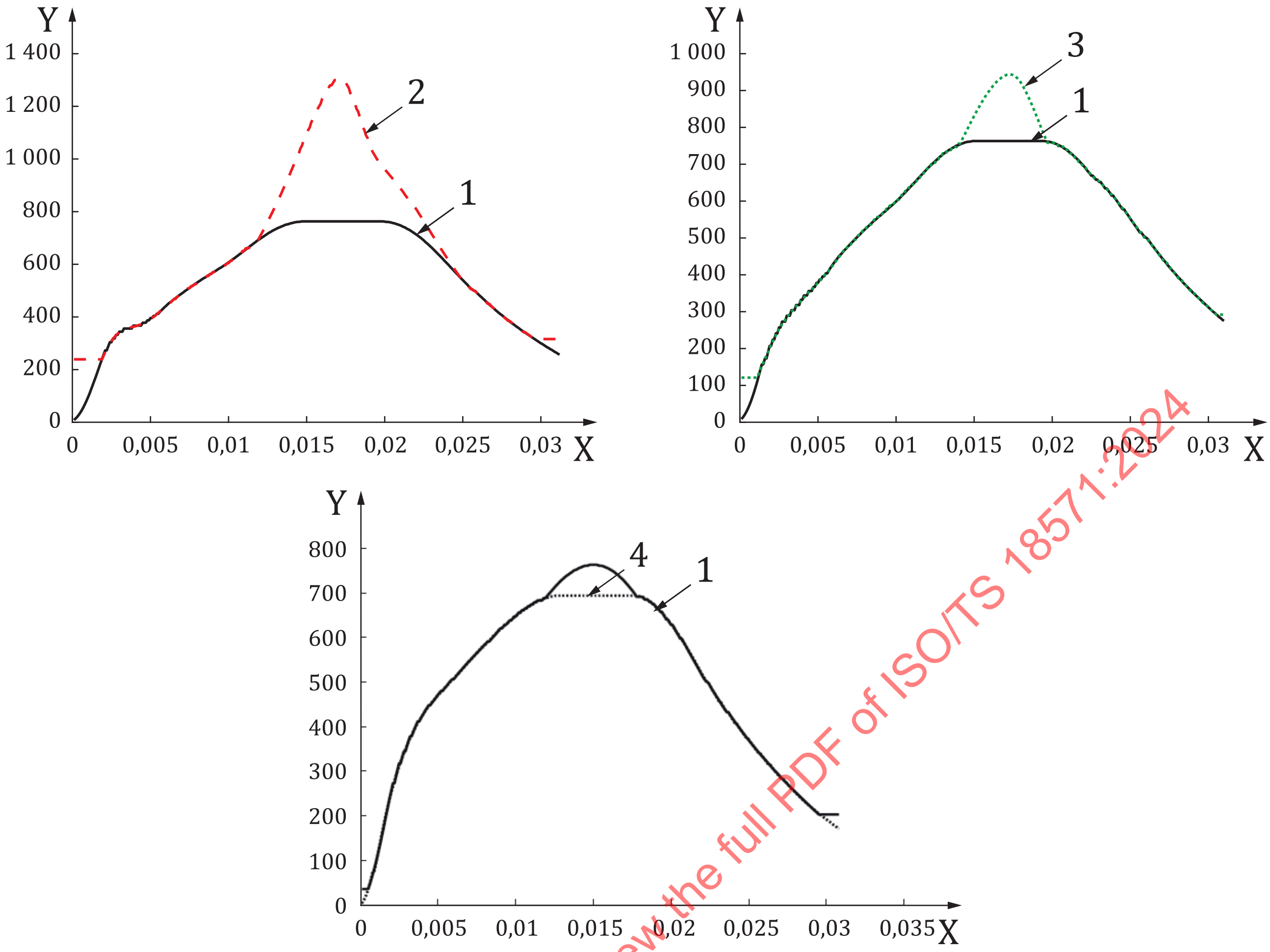
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.5.4 — Slope of time shifted curves



Key

X *t*, time [s]

Y *f* , force [N]

1 test warped

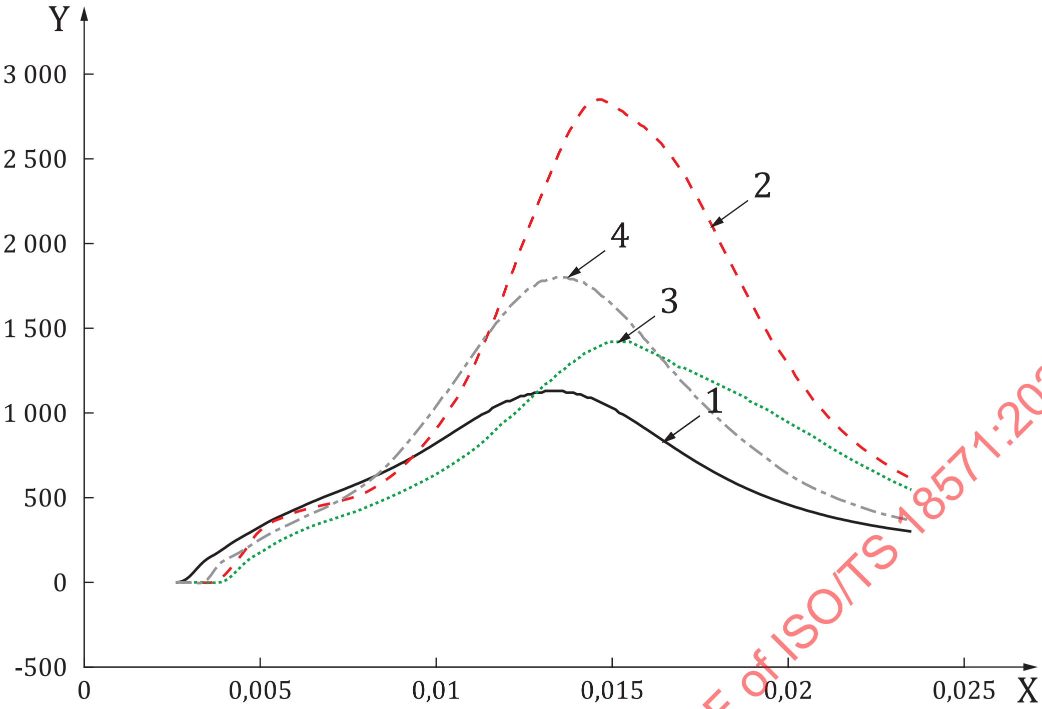
2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.5.5 — Warped time shifted curves

A.5.2 Force 2



Key

X *t*, time [s]

Y *f* , force [N]

1 test

2 CAE1

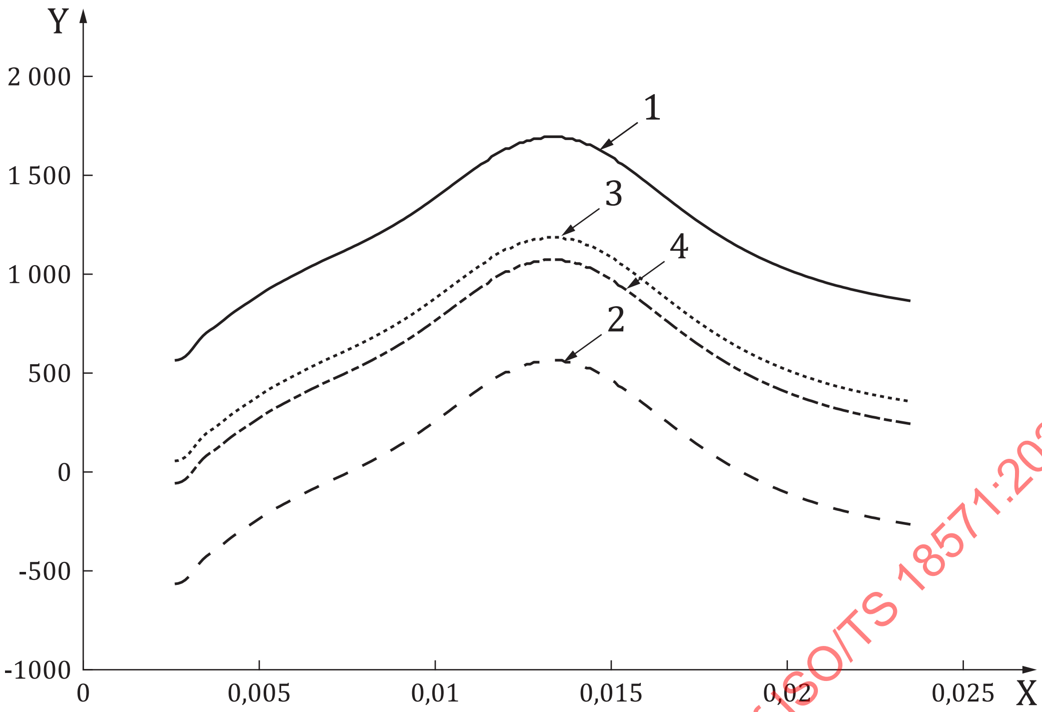
3 CAE2

4 CAE3

Figure A.5.6 — Original curves

Table A.5.2 — ISO rating results

	CAE1 (C_1)	CAE2 (C_2)	CAE3 (C_3)
Grade	Poor	Poor	Fair
Overall rating R	0,276 1	0,576 6	0,646 3
Corridor score Z	0,375 3	0,427 7	0,521 4
Phase score E_P	0,523 8	0,381 0	0,881 0
Magnitude score E_M	0,000 0	0,839 0	0,658 2
Slope score E_S	0,106 0	0,807 9	0,649 8



Key

X *t*, time [s]

Y *f* , force [N]

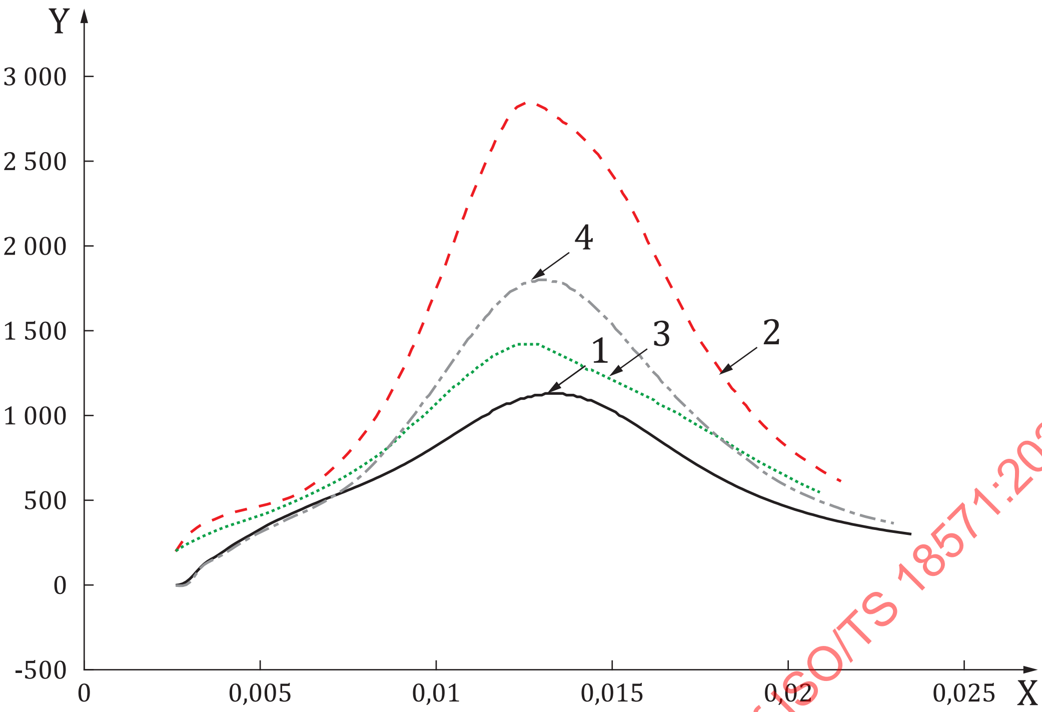
1 outer corridor upper

2 outer corridor lower

3 inner corridor upper

4 inner corridor lower

Figure A.5.7 — Corridor curves



Key

X *t*, time [s]

Y *f* , force [N]

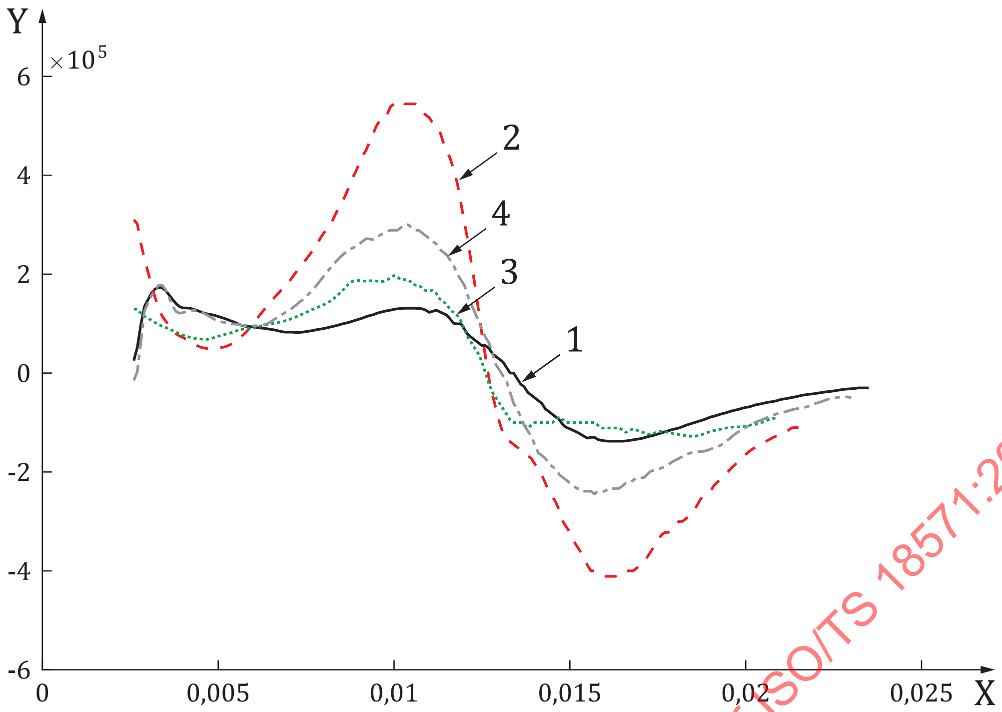
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.5.8 — Time shifted curves



Key

X *t*, time [s]

Y ω , slope of force curve [N/s]

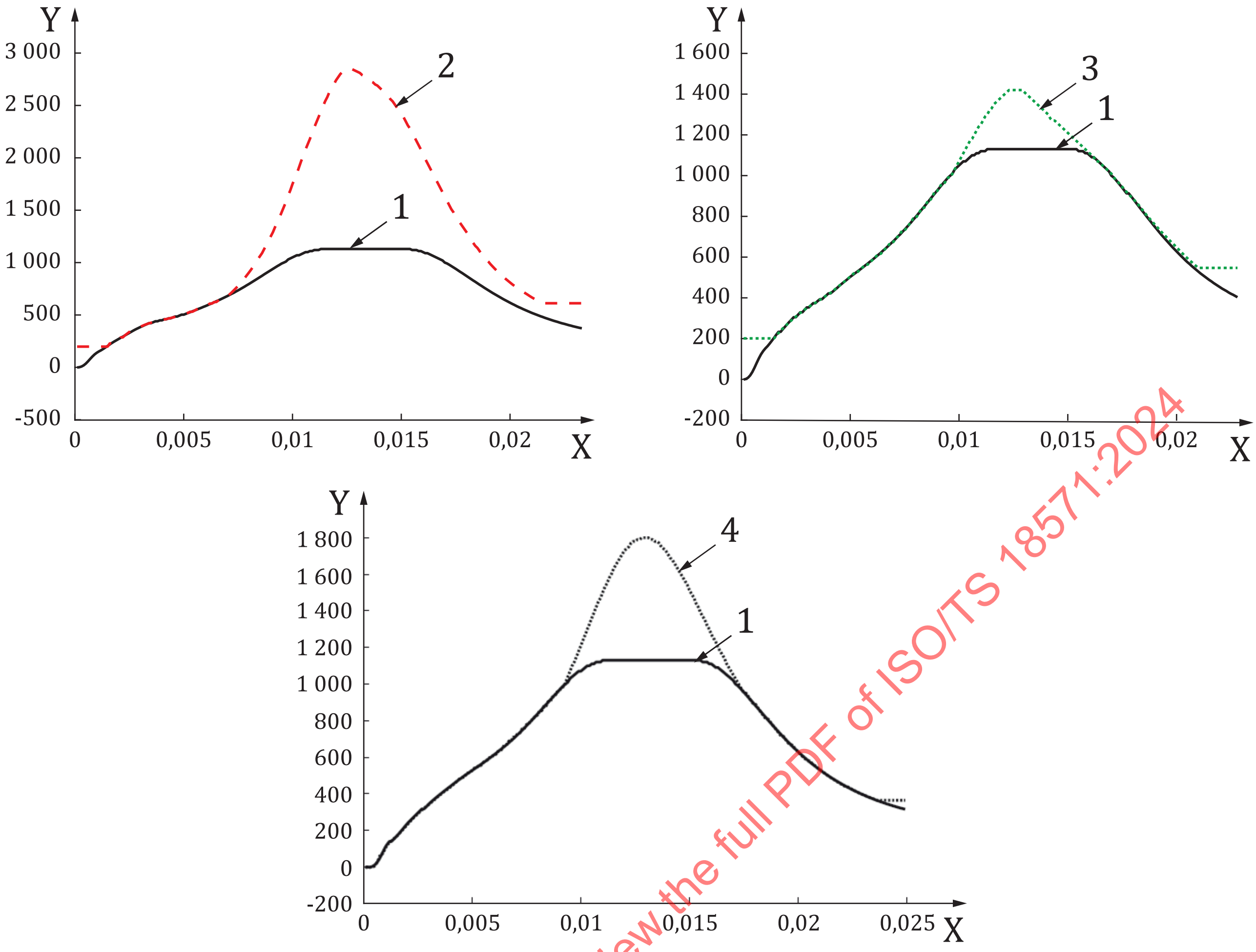
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.5.9 — Slope of time shifted curves



Key

X *t*, time [s]

Y *f* , force [N]

1 test warped

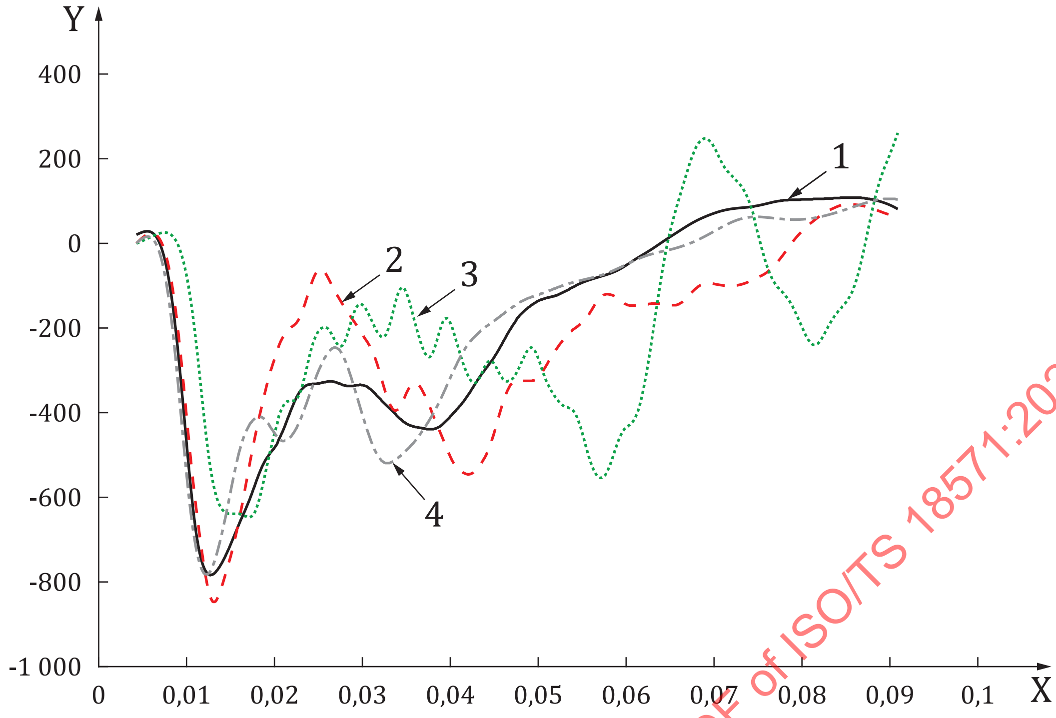
2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.5.10 — Warped time shifted curves

A.5.3 Force 3



Key

X *t*, time [s]

Y *f* , force [N]

1 test

2 CAE1

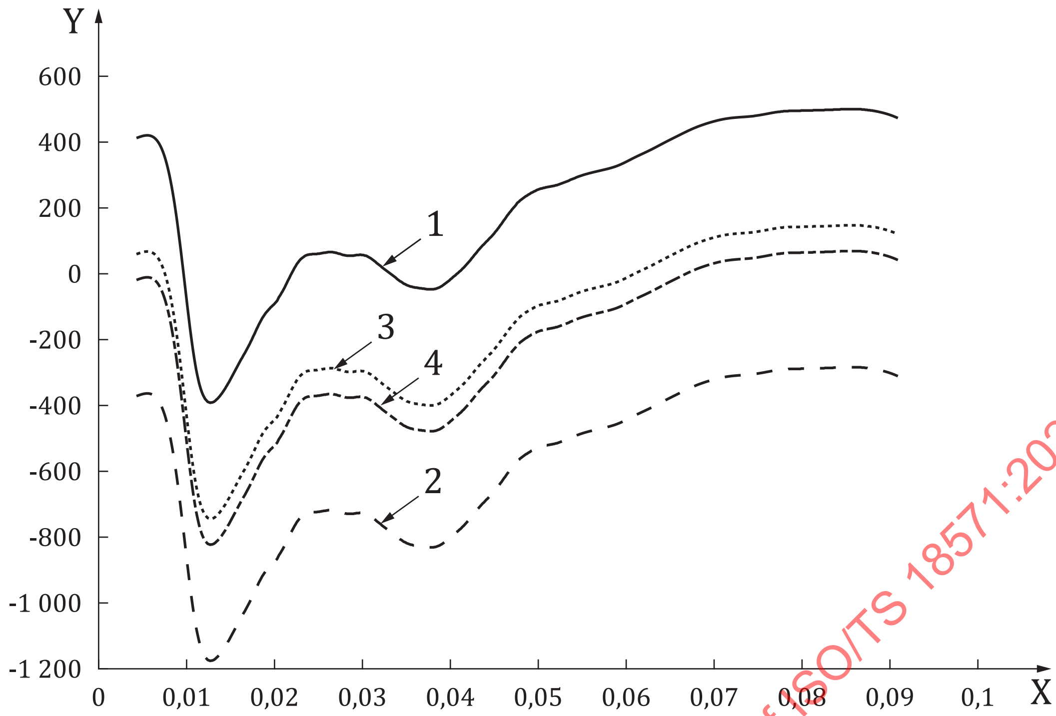
3 CAE2

4 CAE3

Figure A.5.11 — Original curves

Table A.5.3 — ISO rating results

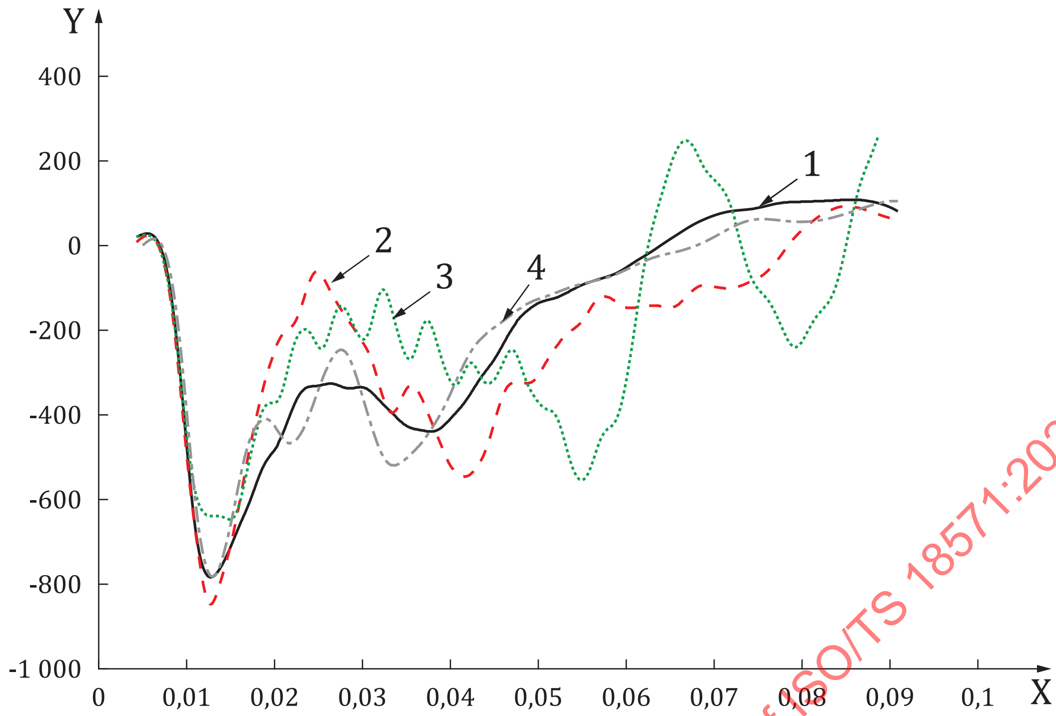
	CAE1 (C_1)	**CAE2 (C_2)**	**CAE3 (C_3)**
Grade	Fair	Poor	Good
Overall rating R	0,713 3	0,465 8	0,864 2
Corridor score Z	0,654 8	0,491 0	0,903 2
Phase score E_P	0,976 9	0,873 1	0,959 6
Magnitude score E_M	0,738 4	0,362 8	0,928 2
Slope score E_S	0,541 4	0,110 9	0,626 9



Key

X	*t*, time [s]
Y	*f* , force [N]
1	outer corridor upper
2	outer corridor lower
3	inner corridor upper
4	inner corridor lower

Figure A.5.12 — Corridor curves



Key

X *t*, time [s]

Y *f* , force [N]

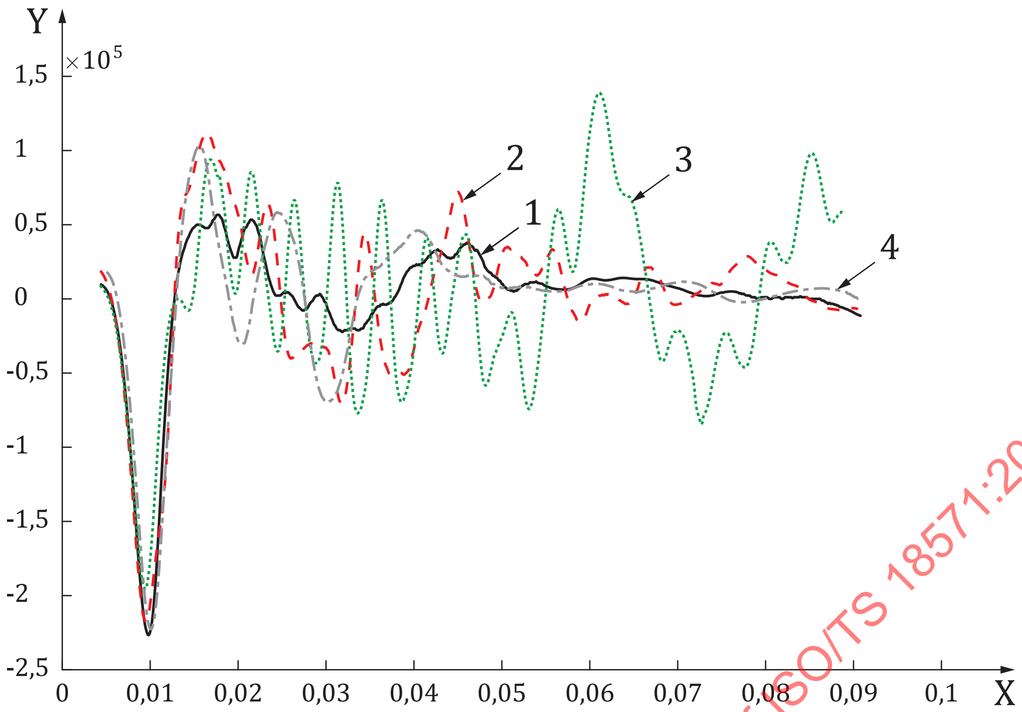
1 test

2 CAE1 phase shifted

3 CAE2 phase shifted

4 CAE3 phase shifted

Figure A.5.13 — Time shifted curves



Key

X *t*, time [s]

Y ω, slope of force curve [N/s]

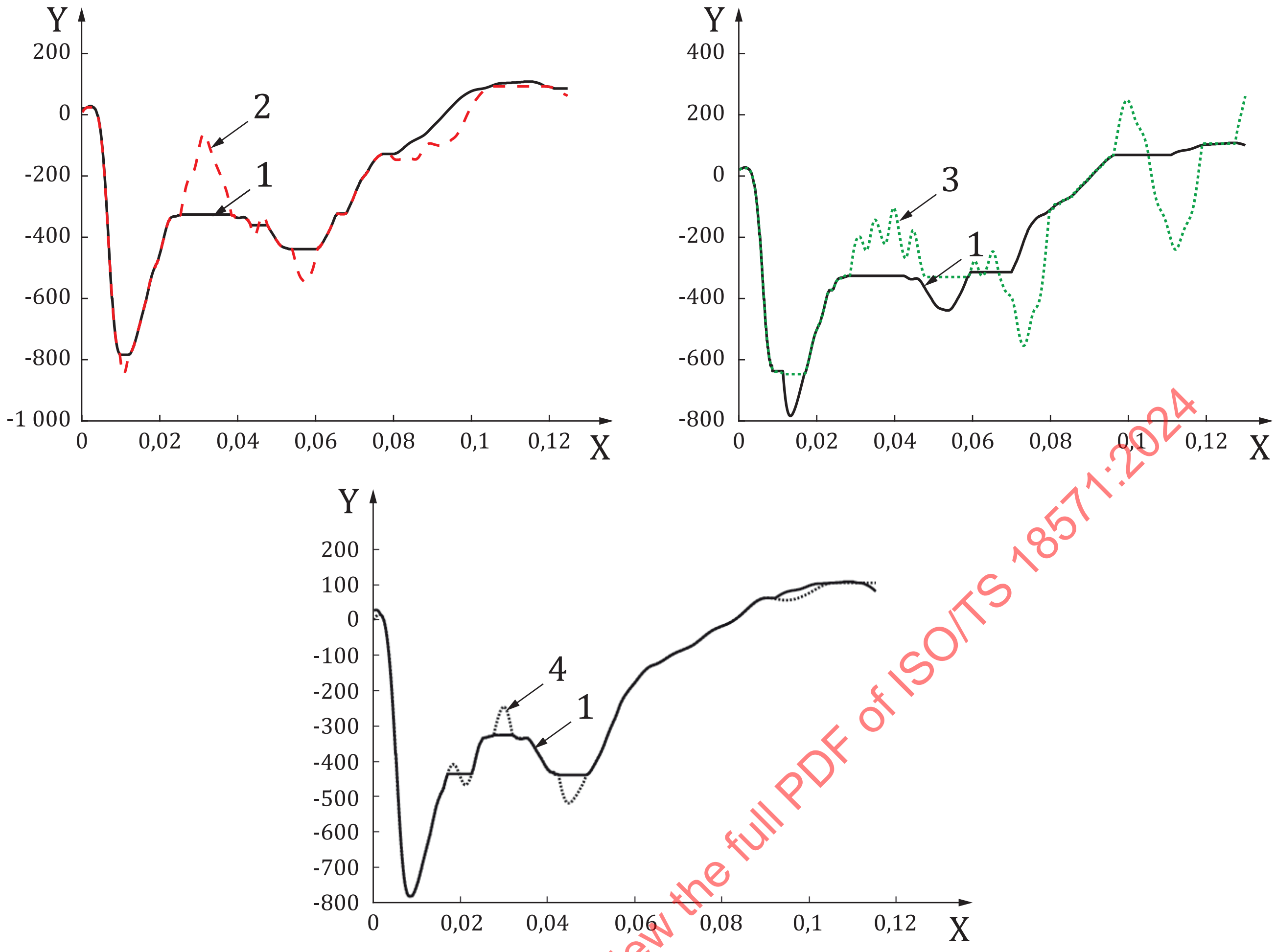
1 test slop

2 CAE1 slop

3 CAE2 slop

4 CAE3 slop

Figure A.5.14 — Slope of time shifted curves



Key

X *t*, time [s]

Y *f* , force [N]

1 test warped

2 CAE1 warped

3 CAE2 warped

4 CAE3 warped

Figure A.5.15 — Warped time shifted curves