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Methods for the calibration of vibration and shock transducers —

Part 11: **Primary vibration calibration by laser interferometry**

Méthodes pour l'étalonnage des transducteurs de vibrations et de chocs —
Partie 11: Étalonnage primaire de vibrations avec interféromètre de laser

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this part of ISO 16063 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 16063-11 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 3, *Use and calibration of vibration and shock measuring instruments*.

This first edition of ISO 16063-11 cancels and replaces ISO 5347-1, which has been technically revised.

ISO 16063 consists of the following parts, under the general title *Methods for the calibration of vibration and shock transducers*:

— *Part 1: Basic concepts*

— *Part 11: Primary vibration calibration by laser interferometry*

— *Part 12: Primary vibration calibration by the reciprocity method*

— *Part 13: Primary shock calibration using laser interferometry*

— *Part 21: Secondary vibration calibration*

— *Part 22: Secondary shock calibration*

Annexes A and B form a normative part of this part of ISO 16063.

Methods for the calibration of vibration and shock transducers —

Part 11:
Primary vibration calibration by laser interferometry

1 Scope

This part of ISO 16063 specifies the instrumentation and procedure to be used for primary vibration calibration of rectilinear accelerometers (with or without amplifier) to obtain magnitude and phase lag of the complex sensitivity by steady-state sinusoidal vibration and laser interferometry.

It is applicable to a frequency range from 1 Hz to 10 kHz and a dynamic range (amplitude) from 0,1 m/s^2 to 1 000 m/s^2 (frequency-dependent).

These ranges are covered with the uncertainty of measurement specified in clause 2. Calibration frequencies lower than 1 Hz (e.g. 0,4 Hz, which is a reference frequency used in other International Standards) and acceleration amplitudes smaller than 0,1 m/s^2 (e.g. 0,004 m/s^2 at 1 Hz) can be achieved using Method 3 specified in this part of ISO 16063, in conjunction with an appropriate low-frequency vibration generator.

Method 1 (fringe-counting method) is applicable to sensitivity magnitude calibration in the frequency range 1 Hz to 800 Hz and, under special conditions, at higher frequencies (cf. clause 7). Method 2 (minimum-point method) can be used for sensitivity magnitude calibration in the frequency range 800 Hz to 10 kHz (cf. clause 8). Method 3 (sine-approximation method) can be used for magnitude of sensitivity and phase calibration in the frequency range 1 Hz to 10 kHz (cf. clause 9).

Methods 1 and 3 provide for calibrations at fixed acceleration amplitudes at various frequencies. Method 2 requires calibrations at fixed displacement amplitudes (acceleration amplitude varies with frequency).

2 Uncertainty of measurement

The limits of the uncertainty of measurement applicable to this part of ISO 16063 shall be as follows.

a) For the magnitude of sensitivity:

 0,5 % of the measured value at reference conditions;

 $\leqslant$ 1 % of the measured value outside reference conditions.

b) For the phase shift of sensitivity:

 0,5° of the measured value at reference conditions;

 $\leqslant$ 1° of the reading outside reference conditions.

Recommended reference conditions are as follows:

— frequency in hertz: 160, 80, 40, 16 or 8 (or radian frequency ω = 1 000, 500, 250, 100 or 50 radians per second);

— acceleration in metres per second squared (acceleration amplitude or r.m.s. value): 100, 50, 20, 10, 5, 2 or 1.

Amplifier settings shall be selected for optimum performance with respect to noise, distortion and influence from cut-off frequencies.

NOTE The uncertainty of measurement is expressed as the expanded measurement uncertainty in accordance with ISO 16063-1 (referred to in short as uncertainty).

3 Requirements for apparatus

3.1 General

This clause gives recommended specifications for the apparatus necessary to fulfil the scope of clause 1 and to obtain the uncertainties of clause 2.

If desired, systems covering parts of the ranges may be used, and normally different systems (e.g. exciters) should be used to cover all the frequency and dynamic ranges.

NOTE The apparatus specified in this clause covers all devices and instruments required for any of the three calibration methods described in this part of ISO 16063. The assignment to a given method is indicated (cf. Figures 1, 2 and 3).

3.2 Frequency generator and indicator

A frequency generator and indicator having the following characteristics shall be used:

a) uncertainty of frequency: maximum 0,05 % of reading;

b) frequency stability: better than ± 0,05 % of reading over the measurement period;

c) amplitude stability: better than ± 0,05 % of reading over the measurement period.

3.3 Power amplifier/vibrator combination

A power amplifier/vibrator combination having the following characteristics shall be used.

a) Total harmonic distortion of acceleration: 2 % maximum.

b) Transverse, bending and rocking acceleration: sufficiently small to prevent excessive effects on the calibration results. At large amplitudes, preferably in the low-frequency range from 1 Hz to 10 Hz, transverse motion of less than 1 % of the motion in the intended direction may be required; above 10 Hz to 1 kHz, a maximum of 10 % of the axial motion is permitted; above 1 kHz, a maximum of 20 % of the axial motion is tolerated.

c) Hum and noise: 70 dB minimum below full output.

d) Acceleration amplitude stability: better than ± 0,05 % of reading over the measurement period.

The attachment surface shall introduce minimal base strain to the accelerometer (see 3.15).

3.4 Seismic block(s) for vibrator and laser interferometer

The vibrator and the interferometer shall be mounted on the same heavy block or on two different heavy blocks so as to prevent relative motion due to ground motion, or to prevent the reaction of the vibrator's support structure from having excessive effects on the calibration results.

When a common seismic block is used, it should have a mass at least 2 000 times the moving mass. This causes less than 0,05 % re-active vibration of accelerometer and interferometer. If the mass of the seismic block is smaller, its motion generated by the vibrator shall be taken into account.

To suppress disturbing effects of ground motion, the seismic block(s) used in the frequency range from 10 Hz to 10 kHz should be suspended on damped springs designed to reduce the uncertainty component due to these effects to less than 0,1 %.

3.5 Laser

A laser of the red helium-neon type shall be used.

Under laboratory conditions (i.e. at an atmospheric pressure of 100 kPa, temperature of 23 °C and relative humidity of 50 %), the wavelength is 0,632 81 µm, which is the value used in this part of ISO 16063.

If the laser has manual or automatic atmospheric compensation, this shall be set to zero or switched off.

Alternatively, a single-frequency laser may be used with another stable wavelength of known value.

3.6 Interferometer

An interferometer of the Michelson type shall be used, with a light detector for sensing the interferometer signal bands and having a frequency response covering the necessary bandwidth.

The maximum bandwidth needed can be calculated from the velocity amplitude, v_{max}, which has to be measured using

$$f_{max} = v_{max} \times 3{,}16 \times 10^6 \text{ m}^{-1}$$

For Method 1 (see Figure 1) and Method 2 (see Figure 2), a common Michelson interferometer with a single light detector is sufficient. For Method 3 (see Figure 3), a modified Michelson interferometer, with quadrature signal outputs, with two light detectors for sensing the interferometer signal beams, shall be used. The modified Michelson interferometer may be constructed according to Figure 4. A quarter wavelength retarder converts the incident, linearly polarized light into two measuring beams with perpendicular polarization states and a phase shift of 90°. After interfering with the linearly polarized reference beam, the two components with perpendicular polarization shall be separated in space using appropriate optics (e.g. a Wollaston prism or a polarizing beamsplitter), and detected by two photodiodes.

The two outputs of the modified Michelson interferometer shall have offsets of less than ± 5 % in relation to the amplitude, relative amplitude deviations of less than ± 5 % and deviations of less than ± 5° from the nominal angle of 90°. To keep these tolerances, appropriate means shall be provided for adjusting the offset, the signal level and the angle between the two interferometer signals.

At large displacements, it may be difficult to maintain the above-stated tolerances for the deviations of the two outputs of the modified Michelson interferometer. To comply with the uncertainty of measurement of clause 2, the above tolerances shall be kept at least for small displacement amplitudes up to 2 µm. Greater tolerances are permitted for higher amplitudes.

EXAMPLE For a displacement amplitude of 2,5 mm (i.e. acceleration amplitude of 0,1 m/s^2 at a frequency of 1 Hz), the tolerances may be extended to ± 10 % for the offsets and for the relative amplitude deviations, and to ± 20° for the deviation from the nominal angle of 90° (see also note 1 of 9.2).

NOTE The (modified) Michelson interferometer for Method 1, 2 or 3 may be replaced by another suitable two-beam interferometer, e.g. a (modified) Mach-Zehnder interferometer.

3.7 Counting instrumentation (for Method 1)

Counting instrumentation (for Method 1) having the following characteristics shall be used.

a) Frequency range: 1 Hz to the maximum needed frequency. (Typically 20 MHz is used.)

b) Maximum uncertainty: 0,01 % of reading.

The counter may be replaced by a ratio counter having the same uncertainty.

3.8 Tunable bandpass filter or spectrum analyser (for Method 2)

A tunable bandpass filter or spectrum analyser (for Method 2) having the following characteristics shall be used.

a) Frequency range: 800 Hz to 10 kHz.

b) Bandwidth: < 12 % of centre frequency.

c) Filter slopes: greater than 24 dB per octave.

d) Signal-to-noise ratio: greater than 70 dB below maximum signal.

e) Dynamic range: greater than 60 dB.

3.9 Instrumentation for zero detection (for Method 2)

Instrumentation for zero detection (for Method 2, not needed with spectrum analyser), with a frequency range from 800 Hz to 10 kHz shall be used. The range shall be sufficient for the detection of output noise from the bandpass filter.

3.10 Voltage instrumentation, measuring true r.m.s. accelerometer output

Voltage instrumentation, measuring true r.m.s. accelerometer output, having the following characteristics shall be used.

a) Frequency range: 1 Hz to 10 kHz.

b) Maximum uncertainty: 0,1 % of reading.

The r.m.s. value shall be multiplied by a factor of $\sqrt{2}$ to obtain the (single) amplitude used in the formulae.

For Methods 1 and 2, a r.m.s. voltmeter shall be used. For Method 3, a special voltage measuring instrumentation according to 3.13 shall be used; a r.m.s. voltmeter may be applied in addition (optionally).

3.11 Distortion-measuring instrumentation

Distortion-measuring instrumentation, capable of measuring total harmonic distortion of << 1 % to 5 % and having the following characteristics shall be used.

a) Frequency range: 1 Hz to 10 kHz with the capability of measuring up to the 5th harmonic.

b) Maximum uncertainty: 10 % of reading in the distortion range 0,5 % to 5 %.

3.12 Oscilloscope (optional)

An oscilloscope for optimizing the interferometer and for checking the waveform of the interferometer and accelerometer signals, with a frequency range from 1 Hz to minimum 2 MHz, may be used.

3.13 Waveform recorder with computer interface (for Method 3)

A waveform recorder with a computer interface (for Method 3), capable of analog-to-digital conversion and storage of the two interferometer quadrature outputs and the accelerometer output shall be used. The amplitude resolution, the sampling rate and the memory shall be sufficient for calibration in the intended amplitude range with the uncertainty specified in clause 2. Typically, an amplitude resolution of $\geqslant$ 10 bits is used for the accelerometer output. For the interferometer quadrature signal outputs, a resolution of $\geqslant$ 8 bits is sufficient. A two-channel waveform recorder may be used for the interferometer output signals, and another waveform recorder (with higher resolution and lower sampling rate) for the accelerometer output signal. In each case, conversion of the data from the interferometer and the accelerometer output signals shall begin and end at the same point in time, with an uncertainty appropriate for the calibration measurement uncertainty requirements of clause 2.

A sufficient number of samples (cf. 9.3) is required of the shortest period of the interferometer output signal that occurs at maximum velocity. For a given acceleration amplitude, at decreasing frequencies, larger displacement amplitudes occur which require that higher sampling rates and larger memories be applied. If such capabilities are not available, the acceleration amplitude shall be reduced.

EXAMPLE To calibrate an accelerometer at a vibration frequency of 1 Hz and an acceleration amplitude of 0,1 m/s^2, a memory of $\geqslant$ 4 Mbytes should be used if a sampling frequency of $\geqslant$ 512 kHz is applied.

3.14 Computer with data-processing program (for Method 3)

A computer with data-processing program (for Method 3) in accordance with the procedure for the calculations stated in 9.4 shall be used.

3.15 Other requirements

In order to achieve the required measurement uncertainty of 0,5 %, the accelerometer and the accelerometer amplifier should preferably be considered as a single unit and calibrated together.

The accelerometer shall be structurally rigid. The base strain sensitivity, the transverse sensitivity and the stability of the accelerometer/amplifier combination shall be taken into account in the calculation of the uncertainty of measurement (cf. annex A).

If a back-to-back reference accelerometer is calibrated, its sensitivity (magnitude and/or phase shift) shall be measured with a dummy mass that is the equivalent of the mass of the transducer to be calibrated by the comparison method (cf. ISO 16063-21) using the back-to-back reference accelerometer. Typically, a 20 g mass is used. The laser light spot can be at either the top (outer surface) of the dummy mass or the top surface of the reference accelerometer.

If the motion is sensed at the top of the dummy mass, then the dummy mass should have an optically polished top surface, and the position of the laser-light spot should be close to the geometrical centre of this surface. In cases where the motion of the mass departs from that of a rigid body, the relative motion between the top (sensed) and bottom surfaces shall be taken into consideration. To simulate a mass of 20 g of typical transfer standard accelerometers, a dummy mass in the form of a hexagonal steel bar 12 mm in length and 16 mm in width over flats of hexagonal faces can be used. At a frequency of 5 kHz, for example, the relative motion introduces systematic errors of 0,26 % in amplitude measurements and 4,2° in phase shift measurements.

When the motion is sensed at the top surface of the reference accelerometer via longitudinal holes in the dummy mass, there may be acoustic resonances that occur in the holes at particular frequencies that influence (increase) the uncertainty of measurements made at, or near, those frequencies. These influences shall be included in the uncertainty calculation.

4 Ambient conditions

Calibration shall be carried out under the following ambient conditions:

a) room temperature, (23 ± 3) °C;

b) relative humidity, 75 % max.

Care should be taken that extraneous vibration and noise do not affect the quality of measurements.

5 Preferred accelerations and frequencies

The accelerations (amplitude or r.m.s. value) and frequencies equally covering the accelerometer range should preferably be chosen from the following series.

a) Acceleration (Methods 1 and 3), in metres per second squared:

— 0,1, 0,2, 0,5, 1, 2, 5, 10, 20, 50, 100, 200, 500, 1 000 (1 000 m/s^2 is valid for amplitude only).

b) Frequency, in hertz:

— selected from the standardized one-third-octave frequency series (ISO 266) between 1 Hz and 10 kHz (or the series of radian frequencies evolving from ω = 1 000 radians per second).

6 Common procedure for all three methods

For every combination of frequency and acceleration, the distortion, the transverse, bending and rocking accelerations, hum and noise shall be at a level to meet the uncertainty requirements of clause 2 (cf. 3.3).

The settings of the accelerometer amplifier (gain and frequency range) shall be set and recorded according to the calibration requirements.

7 Method 1: Fringe-counting method

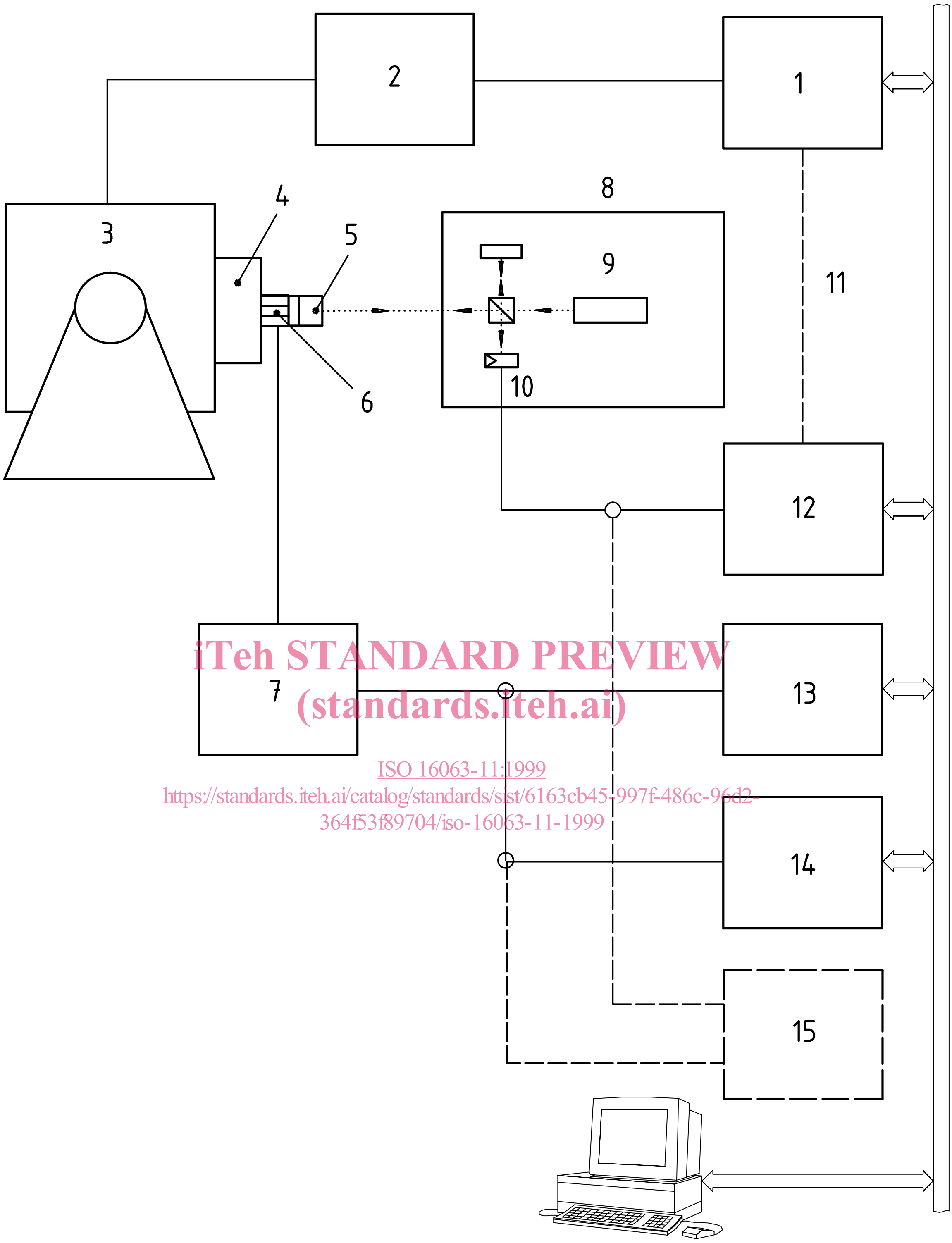
7.1 General

This method is applicable to sensitivity magnitude calibration in the frequency range from 1 Hz to 800 Hz.

NOTE Method 1 may also be applied at higher frequencies if the quantization error is suppressed by special means (see references [2] and [4]). This allows a calibration at a given acceleration amplitude (e.g. 100 m/s^2) to be performed at higher frequencies.

7.2 Test procedure

After optimizing the interferometer (see 3.6), determine the sensitivity at the vibration frequencies and acceleration amplitudes demanded (see clause 5) by measuring either the fringe frequency with the counter (3.7) (the fringe-counting method in accordance with Figure 1 shall be used) or the ratio between the vibration frequency and the fringe frequency with a ratio counter (3.7).



Key

1 Frequency generator (3.2)
2 Power amplifier (3.3)
3 Vibrator (3.3)
4 Moving part of vibrator
5 Dummy mass
6 Accelerometer
7 Amplifier
8 Interferometer (3.6)
9 Laser (3.5)
10 Light detector
11 With ratio counter (3.7)
12 Counter (or ratio counter) (3.7)
13 Voltmeter (3.10)
14 Distortion meter (3.11)
15 Oscilloscope (3.12)

Figure 1 — Measuring system for the fringe-counting method (Method 1)

7.3 Expression of results

See B.1, annex B.

Calculate the acceleration amplitude, $\hat{a}$, of the accelerometer, expressed in metres per second squared, from the fringe frequency readings using the following formula:

$$\hat{a} = f\, f_{\mathrm{f}} \times 3{,}123 \times 10^{-6}\ \mathrm{m}$$

and calculate the sensitivity (magnitude), S, expressed in volts per metre per second squared, from the following formula:

$$S = \frac{\hat{u}}{f\, f_{\mathrm{f}}} \times 0{,}3202 \times 10^{6}\ \mathrm{m}^{-1}$$

where

$\hat{u}$ is the accelerometer output voltage amplitude;

f is the frequency of the vibrator;

f_{f} is the fringe frequency, i.e. the number of fringes counted over a sufficiently long time period divided by the time.

If a ratio counter is used, calculate the acceleration amplitude, $\hat{a}$, expressed in metres per second squared, using the following formula:

$$\hat{a} = f^{2} R_{\mathrm{f}} \times 3{,}123 \times 10^{-6}\ \mathrm{m}$$

and calculate the sensitivity (magnitude), S, expressed in volts per metre per second squared, from the following formula:

$$S = \frac{\hat{u}}{f^{2} R_{\mathrm{f}}} \times 0{,}3202 \times 10^{6}\ \mathrm{m}^{-1}$$

where R_{f} is the ratio of the fringe frequency, f_{f}, to the vibration frequency, f, over a sufficient number of vibration periods (frequency-dependent, e.g. at least 100 vibration periods at 160 Hz).

When the calibration results are reported, the expanded uncertainty of measurement in the calibration shall be calculated and reported in accordance with annex A.

8 Method 2: Minimum-point method

8.1 General

This method is applicable to sensitivity magnitude calibration in the frequency range from 800 Hz to 10 kHz.

NOTE The method illustrated in this clause is based on the determination of displacement using the arguments corresponding to the zero crossings of the Bessel function of the first kind and first order (see B.2, annex B). An equally valid approach is to determine displacement using the arguments corresponding to the zero crossings of the Bessel function of the first kind and zero order. However, this technique requires modulation of the position of the reference mirror in order to be implemented (see reference [5]).

