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Cooled and uncooled single-channel deformable mirrors for industrial laser systems

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Abstract. A study was made of bimorph mirrors intended for industrial laser systems. The technical characteristics of cooled single-channel deformable mirrors were investigated in detail. Preliminary tests were made on uncooled bimorph mirrors in industrial laser systems based on a cw CO_2 laser with an output power in excess of 2 kW and on a pulsed copper vapour laser with an average power of 35 W.

1. Introduction

Extensive and intensive use of lasers of various types (CO_2 lasers, $\lambda = 10.6$ μm; Nd : YAG lasers, $\lambda = 10.6$ μm, etc.) in the manufacturing industry, and particularly in automobile production [1, 2], is complicating increasingly laser processing technologies. Their functional capabilities are gradually widening and this is accompanied by a simultaneous increase in the rate at which they perform industrial operations and in the processing quality. The next step in the improvement of laser technologies is the use of controlled (adaptive) optics, particularly of deformable mirrors. In the initial stages it is preferable to use the simplest components and systems.

A whole range of tasks is awaiting such systems in the currently used industrial lasers. On the one hand, there are the traditional tasks performed by adaptive optics, namely an increase in the quality of laser systems by real-time compensation of distortions of the optical radiation such as those caused by the formation of a nonlinear thermal lens, etc. On the other hand, there are some specific tasks in laser processing technologies, for example, real-time (at the highest possible rate) control of the spatial position of the focal spot of a laser head in the course of welding or cutting of workpieces with complex configurations [3].

Bimorph adaptive optics is of special interest in respect of practical incorporation into existing laser systems. A detailed analysis of the advantages of bimorph adaptive optics is given in Ref. [4] and a full account of the parameters and designs of experimental bimorph mirrors in Ref. [5]. This paper reports an experimental investigation and tests on single-channel deformable bimorph mirrors developed for industrial laser systems intended for a variety of purposes and differing from the known mirrors [5 – 7] by high and stable technical characteristics, user friendliness, a high reliability, and a low cost.

2. Experimental investigations of cooled deformable mirrors

Uncooled single-channel mirrors of this type, intended for laser systems with an output power up to 1 kW, had been investigated in detail earlier [8]. The bimorph technology [9, 10] developed and used in such mirrors was employed in the fabrication of cooled deformable mirrors made of molybdenum (Fig. 1).

Figure 1. Molybdenum cooled single-channel adaptive mirrors for laser systems with an output power up to 10 kW.

An external diameter of a mirror is 70 mm and its height is 13.7 mm. A 'tilted waffle' cooling system is built-in under the reflecting surface of the mirror. The cooling agent is delivered to this system by metal pipes (Fig. 1). This cooling method makes it possible to employ cooled bimorph mirrors in laser systems with a total output power up to 10 kW. Detailed investigations of this type of cooling system designed specifically for cooled bimorph mirrors are reported in Ref. [11].

The diameter of the illumination zone of such cooled deformable mirrors is 42 mm, the initial shape of the optical surface is plane, the reflecting coating is made of copper, and the protective coating is made of silicon dioxide. The specular reflection coefficient at the $\lambda = 10.6$ μm wavelength is at least 98.5%. The control voltage applied to such cooled bimorph mirrors ranges from -300 V to 200 V. The capacitance of the control electrode is ~ 300 nF and the mass of the mirror is about 300 g.

2.1 Initial shape of the optical surface of cooled deformable mirrors

A Mark-II interferometric system (Fig. 2) was used to investigate cooled deformable mirrors. An interferometer (*1*) is of the familar Fizeau type; the diameter of the output beam is 102 mm, the working wavelength is 632.8 nm, and the laser

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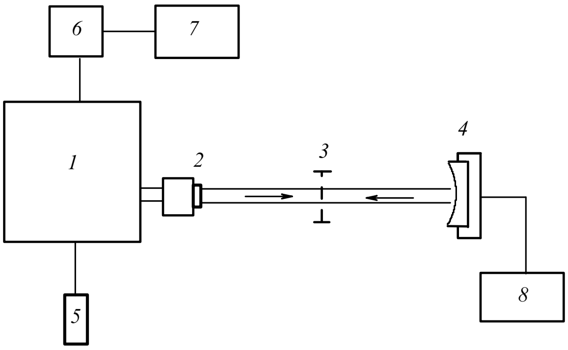

Figure 2. Structural diagram of the measuring system: (*1*) Mark-II interferometer; (*2*) standard plane-parallel plate; (*3*) attenuation filter; (*4*) deformable mirror, attached to a five-coordinate adjustment head; (*5*) control panel of the interferometer; (*6*) VM-2 video monitor; (*7*) P50E video printer; (*8*) electronic unit for control of the deformable mirror.

radiation power is 1 mW. A plane-parallel plate is used as an optical standard (*2*) in measurements on initially plane deformable mirrors. The error in recording the interference pattern by this system, governed by the quality of the optical part of the system, is $\lambda/20$ when monitoring plane optical surfaces and $\lambda/10$ for spherical surfaces.

Determination of the initial shape of the optical surface demonstrated a high quality and high stability of the cooled deformable mirrors. This was confirmed by repeated interferometric monitoring carried out over a period of several months for a variety of air temperatures and humidities, and also after transporting these mirrors under a variety of conditions. A typical interferogram of the initial shape of a cooled deformable mirror is shown in Fig. 3.

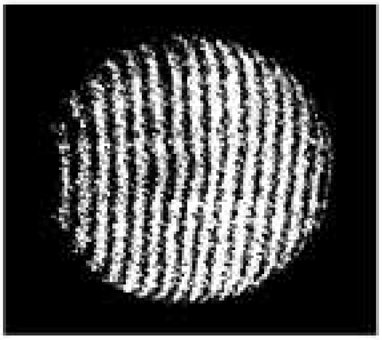

Figure 3. Interferogram of the initial shape of the reflecting surface of a cooled single-channel deformable mirror with a total illumination diameter of 42 mm.

An analysis of a number of such interferograms established that the total deviation of the surface shape from planar over the whole illuminated diameter did not exceed an interference ring $F = \lambda/2$ for the cooled deformable mirrors and the local deviation of the surface shape over the whole illuminated diameter did not exceed $0.25F = \lambda/8$.

2.2 Response functions and sensitivity of cooled adaptive mirrors

The response functions of the cooled bimorph mirrors were determined experimentally employing the automated system described above (Fig. 2). The control voltage was applied to a deformable mirror by an electronic unit (*8*). Fig. 4 shows a typical interferogram of the reflecting surface of a cooled single-channel mirror subjected to the control voltage.

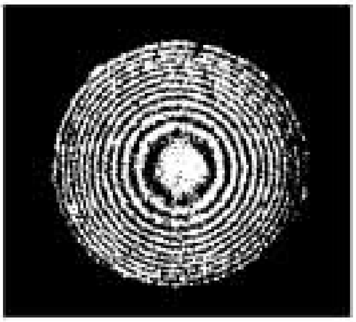

Figure 4. Interferogram of the reflecting surface of a cooled single-channel deformable mirror with a total illumination diameter of 42 mm under a control voltage $U = 80$ V.

Such experimental measurements and their statistical analysis were used to determine the amplitude sensitivity of the cooled adaptive mirrors, which on the average (on the basis of 96 measurements) was 46 ± 8 μm kV^{-1}. One should point out the following. For the bimorph mirrors in general and for the investigated mirrors in particular the sensitivity depends on the sign of the control voltage, which is the result of polarisation of the piezoelectric ceramic used in the system. More specifically, if the sign of the applied control voltage is identical with the sign of the polarisation voltage of this ceramic, the bimorph mirror sensitivity is higher than when the signs of these voltages are opposite. In particular, for the investigated cooled mirrors, the polarisation voltage of the ceramic was negative relative to the body of the mirror, so that for negative voltages the amplitude sensitivity was slightly above the average: 49 ± 6 μm kV^{-1}. Similarly for positive voltages the sensitivity was below the average: 44 ± 8 μm kV^{-1}.

The influence of the polarisation of the ceramic accounts also for the asymmetry of the control voltage range: in the present case, it was shifted to negative values. Subject to this shift, the maximum controlled deformations of the cooled bimorph mirrors were 14.7 μm under a voltage of -300 V (convex shape) and -8.9 μm under a voltage of 200 V (concave shape).

Bearing in mind the points made above, the empirical response function [8] could be written in the following form (ignoring the influence of hysteresis) applicable to the investigated cooled single-channel bimorph mirrors:

$$W(r) = -K\left(\frac{r}{r_1}\right)^2 U\,, \tag{1}$$

where $W(r)$ is the response function of the reflecting surface of the mirror; r_1 is the radius of the reflecting surface (in our case, $r_1 = 21$ mm); K is the sensitivity; U is the control voltage. For the investigated deformable mirrors the value of K was in the range 44 – 49 μm kV^{-1}.

2.3 Hysteresis of cooled deformable mirrors

Piezoelectric adaptive mirrors are characterised by an electromechanical hysteresis, demonstrated by a nonlinear dependence of the displacements of the reflective surface on the applied voltage. The hysteresis of the cooled mirrors was determined as follows. The method described above was used to find, for a range of control voltages, the shape of the reflecting surface of a deformable mirror and its bending was calculated. The control voltage applied to the mirror during measurements was varied in a cyclic manner: $0 \to +U \to 0 \to -U \to 0 \to +U$. The numerical results were used to plot a hysteresis loop and each point on the loop was averaged over four measurements in order to avoid random errors.

Fig. 5 shows the form of a hysteresis loop for a cooled bimorph mirror with the square dots corresponding to the initial part of the dependence $W(U)$. Numerically, the hysteresis is characterised by the ratio of the width of the loop at zero voltage to its total height and, for the investigated deformable mirrors, it is 10.6% ± 0.3%.

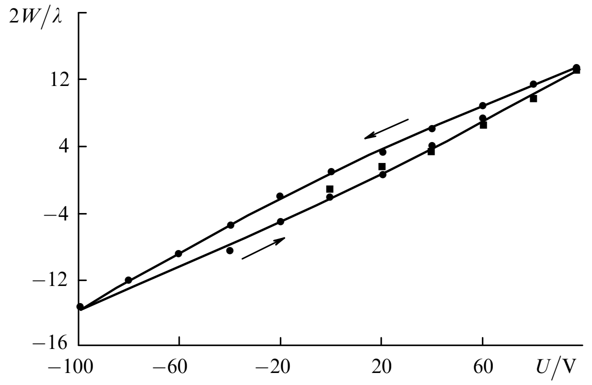

Figure 5. Dependence of the deformation amplitude on the control voltage applied to a cooled single-channel deformable mirror.

3. Preliminary tests on uncooled deformable mirrors

Preliminary tests on uncooled single-channel bimorph mirrors, investigated in detail earlier [8], were made with a cw CO_2 laser and a pulsed copper vapour laser.

3.1 Tests with a CO_2 laser

In spite of the calculated value of the power that can be handled by uncooled bimorph mirrors, which does not exceed 1 kW (and this in the presence of external forced cooling [8]), in our preliminary tests we used a cw industrial CO_2 laser with an output radiation power in excess of 2 kW. This procedure was adopted because of similar geometric parameters of the deformable mirrors and of the intracavity laser optics. The laser was a component of the Garpun-2000 industrial system and its main technical characteristics were as follows:

Radiation wavelength/μm	10.6
Maximum radiation power:	
in multimode regime/W	2500
in single-mode regime/W	1000
Diameter of the output radiation beam:	
in multimode regime/mm	⩽45
in single-mode regime/mm	20
Divergence in single-mode regime/mrad	⩽2
Controlled power range/W	200 – 2000

The tests with the CO_2 laser revealed that, when an uncooled bimorph mirror was placed in an evacuated cavity, its initially plane reflecting surface became deformed (bent), so that the radius of curvature ranged from 9.4 m (over the whole illuminated aperture of 42 mm) to 7.4 m (over an aperture of 7 – 10 mm). In estimating the radius of curvature we used a collimator taken from an OSK-2TsL optical bench. Such deformations of the bimorph mirrors were fully linear and elastic; removal of the pressure restored the initial shape of the reflecting surface. This effect should be taken into account when deformable mirrors are used in evacuated optical systems and the initial reflecting surface has to be corrected for the intracavity static deformation.

Our gas-discharge CO_2 laser with fast axial circulation of the active mixture had a stable cavity an end concave mirror, characterised by a radius of curvature −30 m, and semitransparent output mirrors whose radii of curvature were −30 m (in the multimode lasing regime) and −15 m (in the single-mode regime). The cavity included also plane rotatable mirrors. The whole of the cavity optics was cooled, the diameter of the end and output mirrors was 6 cm, and the total cavity length was 6.5 m.

In this stable cavity of the CO_2 laser we replaced the end mirror with an uncooled bimorph mirror. The radiation power in the cavity was ~260 W. The deformable mirror was not externally cooled. In spite of the strongly nonoptimal cavity geometry and the effect mentioned above, stable lasing was observed. The application of a control signal of a certain value to the deformable mirror stopped lasing because the reflecting surface became deformed.

Optimisation of the parameters of the deformable mirror directly for the cavity employed and the use of cooled bimorph optics described in Section 2 above, should make it possible to Q switch our cw CO_2 laser. The maximum depth of such switching would probably be attainable at the control voltage frequency identical with the frequency of the main resonance of the deformable mirror, because the controlled displacements of its reflecting surface should then be maximal. Under a quasistatic control voltage the use of such deformable mirrors inside the investigated laser should make it possible to control the output power, at least between certain finite limits.

Multilayer bimorph mirrors used in these experiments were subject to a considerable total load on the flexible reflecting plate. This was the result of at least three factors: thermal strains of the mirror under the action of the intracavity radiation, deformation of the reflecting plate by the external (relative to the cavity) atmospheric pressure, and controlled mirror deformation.

3.2 Tests with a copper vapour laser

In these tests we used an ILGI-201 laser, which was part of the Karavella industrial system and which had the following main technical characteristics:

Radiation wavelength/μm	0.51 and 0.58
Radiation divergence/mrad	0.1 – 0.5
Diameter of the output radiation beam/mm	20
Pulse repetition rate/kHz	8 – 12.5
Duration of radiation pulse at half-amplitude/ns	15 ± 5
Radiation power:	
average/W	30 – 35
pulsed/kW	200 – 250

An uncooled single-channel deformable mirror had an illumination aperture 42 mm and a copper reflecting coating.

The specular reflection coefficient at the two wavelengths was 44% ($\lambda = 0.51$ μm) and ~60% ($\lambda = 0.58$ μm).

This deformable mirror was used outside the cavity of the copper vapour laser to control the plane of the waist of the laser beam formed by the optical system with a focal length 7.5 m. The bimorph mirror was placed directly in front of a concave spherical mirror. Variation from +100 V to −200 V of the control voltage applied to the deformable mirror displaced linearly (when account was taken of the electromechanical hysteresis) the beam waist from its average position 2.4 m away from the cavity and by 4.8 m towards the cavity, respectively.

The uncooled bimorph mirror experienced fairly strong heating (approximately to 80 °C) by laser radiation, but its operating characteristics were unchanged. Moreover, the uncooled mirrors operated stably in the presence of laser radiation and were heated to temperatures of the order of 45 – 50 °C. Such thermal regimes were observed because of the very low reflection coefficient of the deformable mirrors at the working wavelength of the laser. The use of suitable reflecting coatings on these uncooled molybdenum bimorph mirrors should ensure their prolonged and efficient operation in this laser at temperatures of the order of 20 – 25 °C.

4. Conclusions

Our experimental investigation of cooled and uncooled multilayer bimorph mirrors, as well as preliminary tests of these mirrors in industrial lasers allow us to consider such mirrors as convenient, reliable, and low-cost instruments for widening the functional capabilities of the existing laser processing systems. The effectiveness of the use of such deformable mirrors should improve at shorter wavelengths of the laser radiation.

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