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(54) **SYSTEMS AND METHODS FOR ENERGY EFFICIENT ELECTROLYSIS CELLS**

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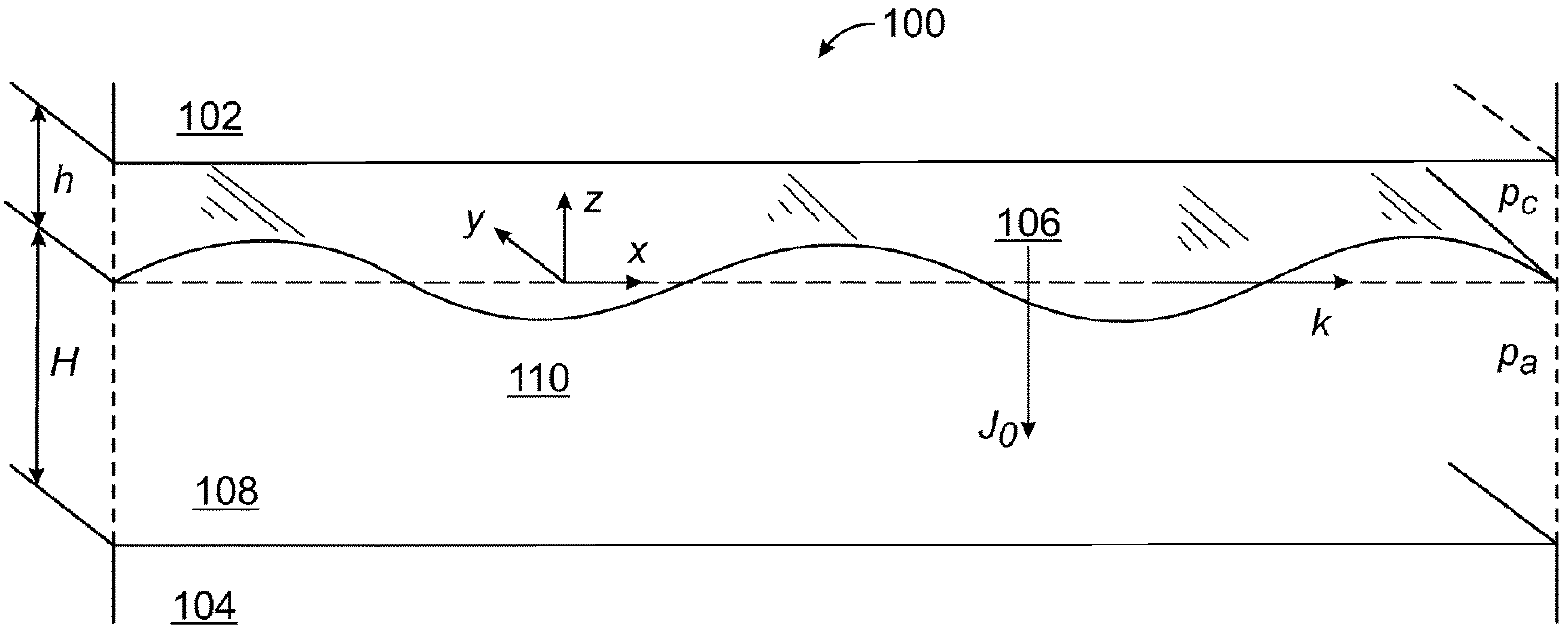
C25C 3/18	(2006.01)
C25C 7/06	(2006.01)

(52) **U.S. Cl.**

CPC ***C25C 3/20*** (2013.01); ***C25C 3/18*** (2013.01); ***C25C 7/06*** (2013.01)

(57) **ABSTRACT**

Disclosed herein are systems and methods for obtaining efficient aluminum smelters. More specifically disclosed herein is a method comprising: applying an alternating current (AC) comprising an oscillatory current waveform to an electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis. Also disclosed herein is a system comprising an electrolytic cell, direct current and alternating current sources. The disclosed electrolytic cell exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell.



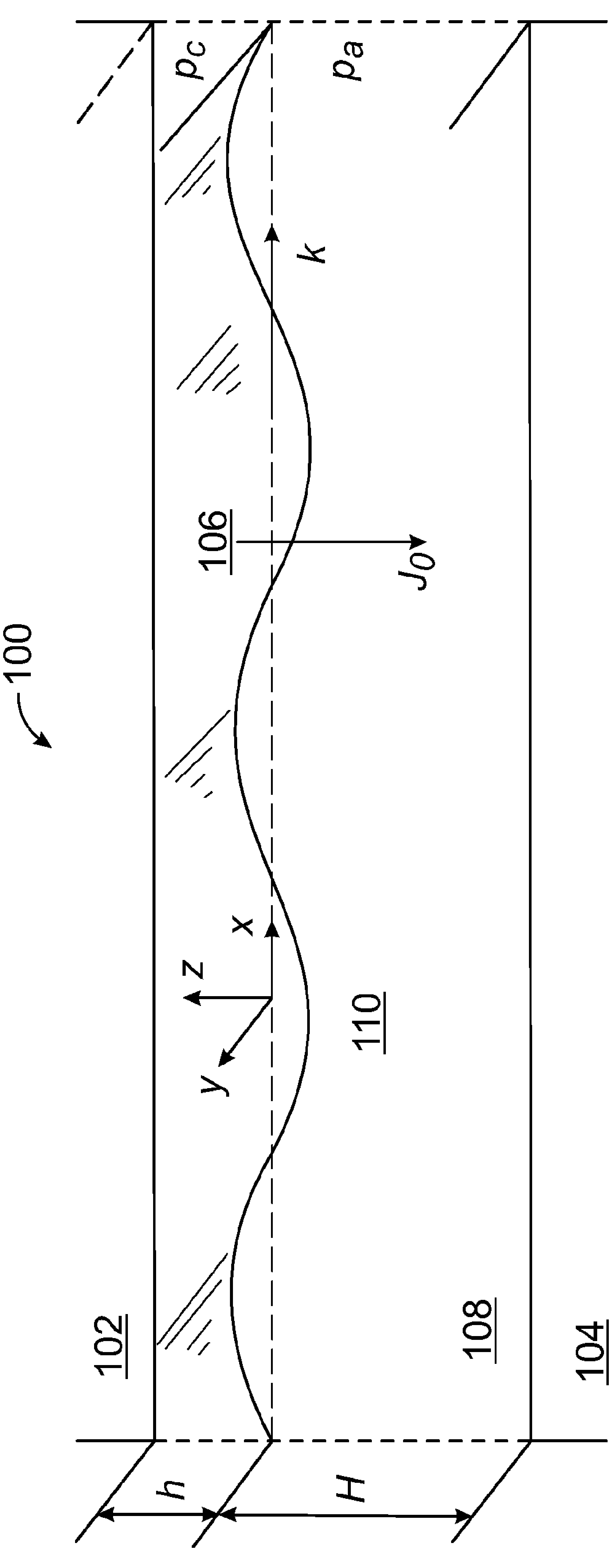


FIG. 1

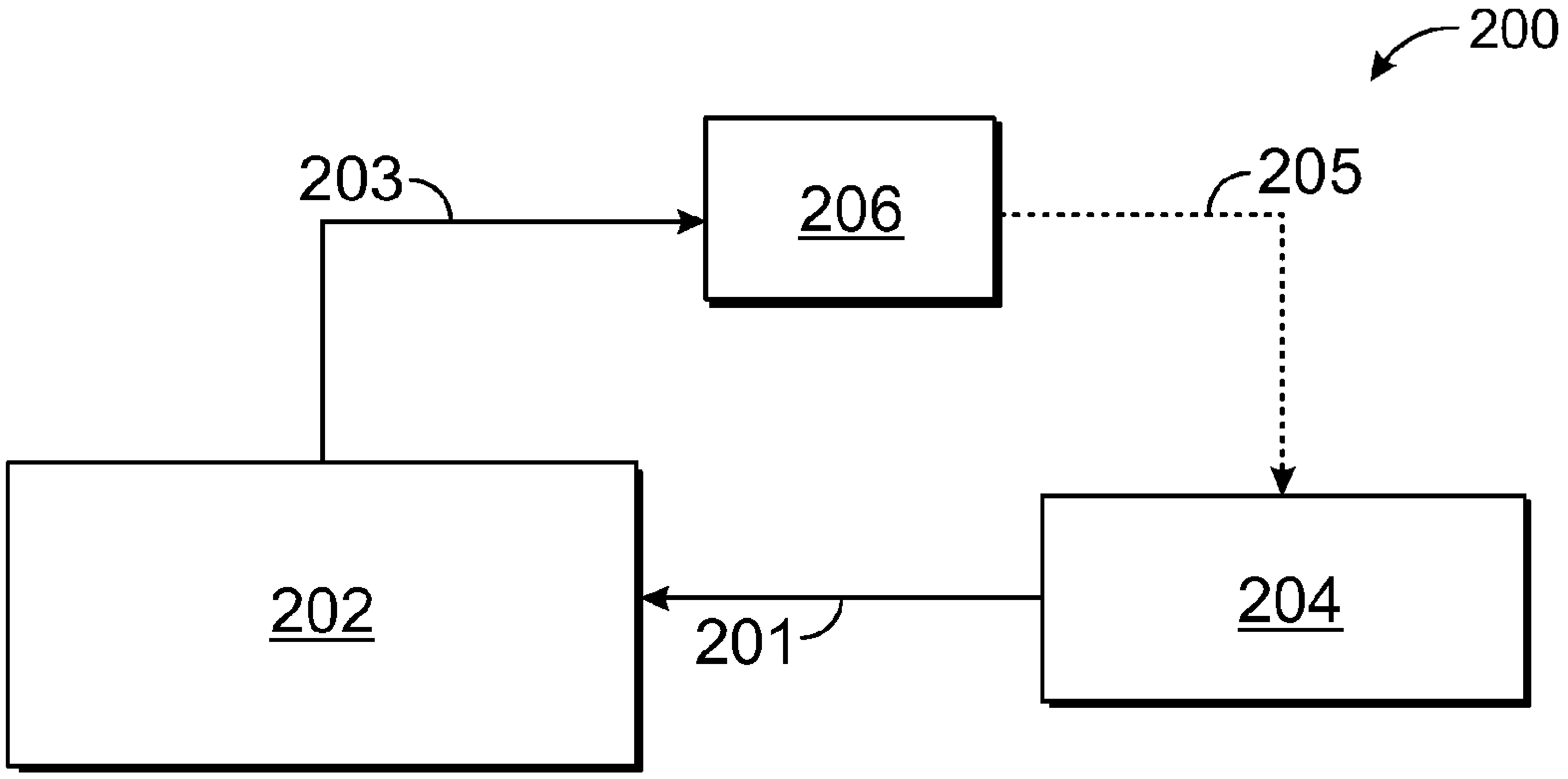


FIG. 2

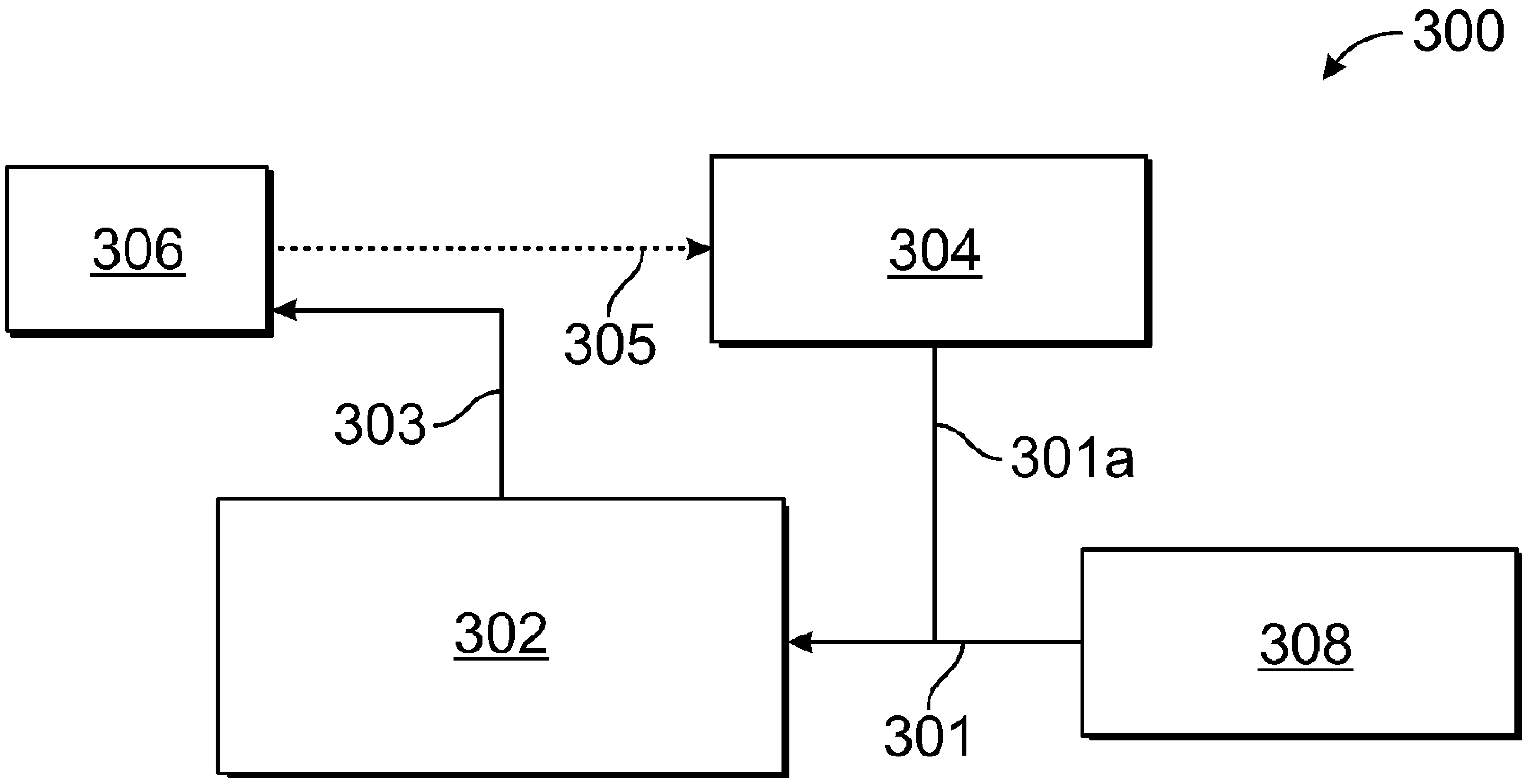


FIG. 3

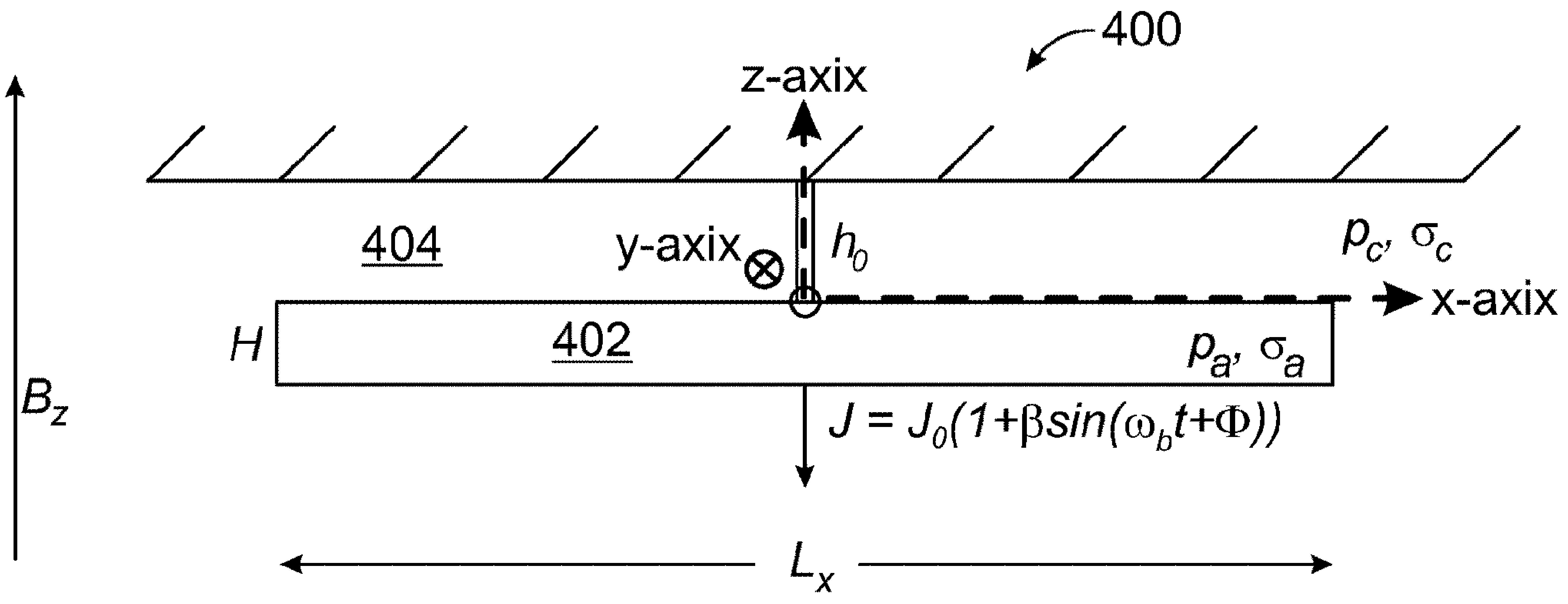

400
z-axix
404
y-axix
h_0
p_c, σ_c
x-axix
H
402
p_a, σ_a
B_z
$J = J_0(1+\beta sin(\omega_b t+\Phi))$
L_x

FIG. 4

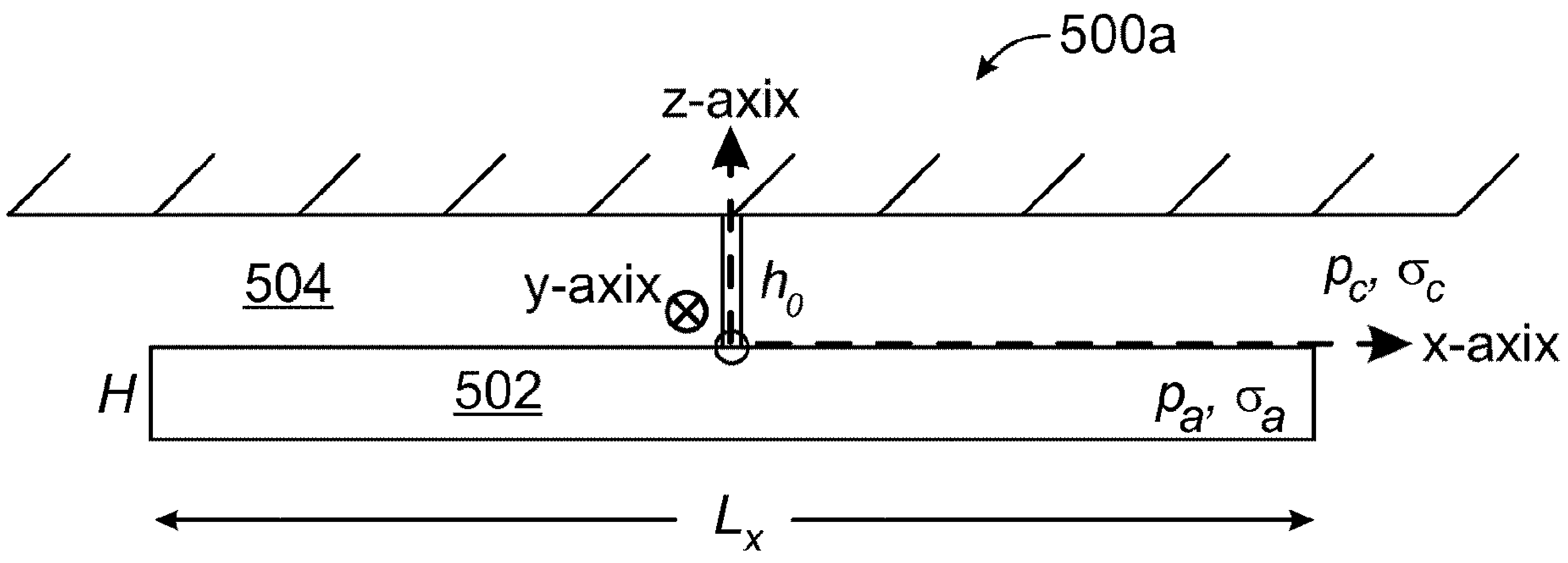

500a
z-axix
504
y-axix
h_0
p_c, σ_c
x-axix
H
502
p_a, σ_a
L_x

FIG. 5A

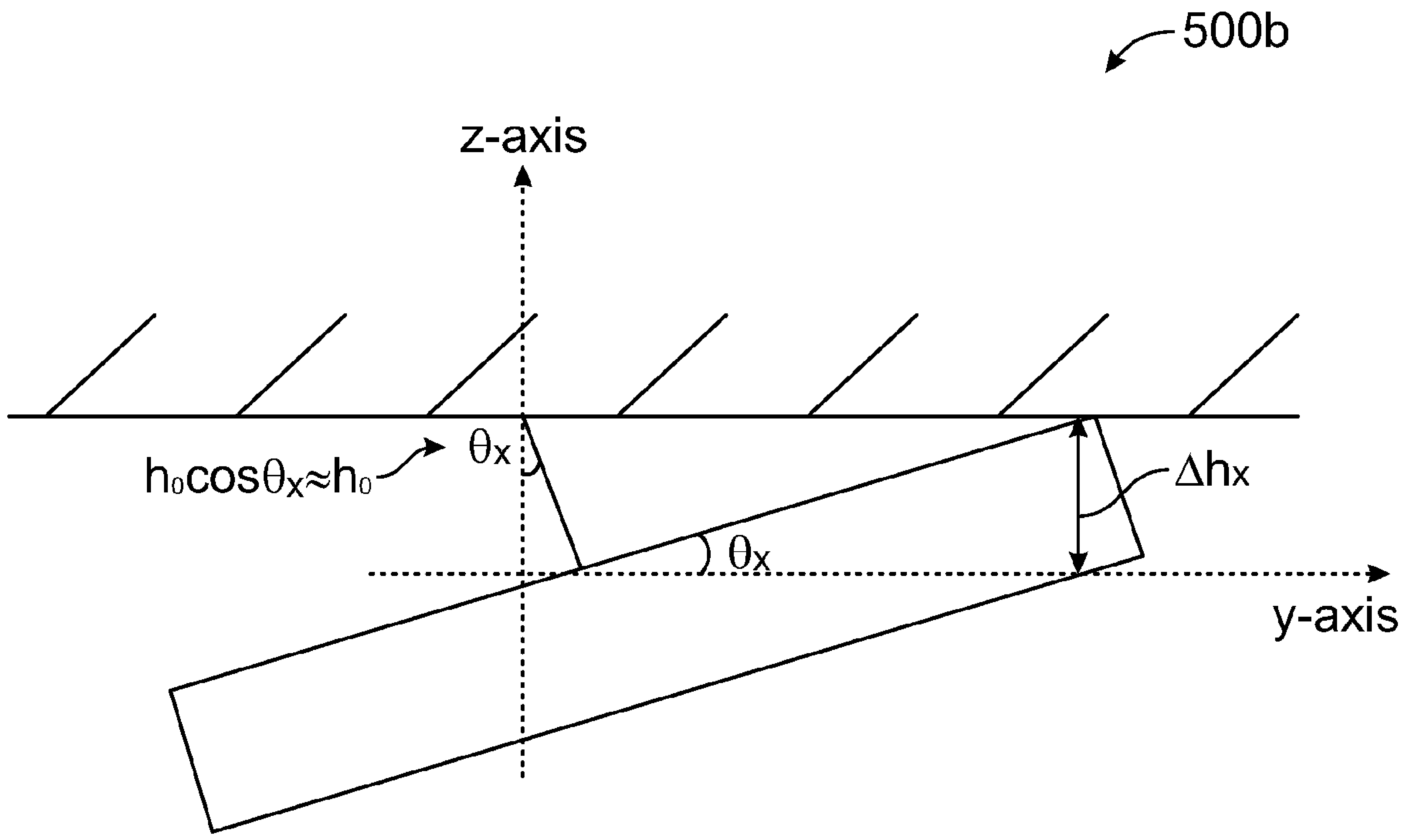

500b
z-axis
$h_0\cos\theta_x \approx h_0$
θ_x
Δh_x
θ_x
y-axis

FIG. 5B

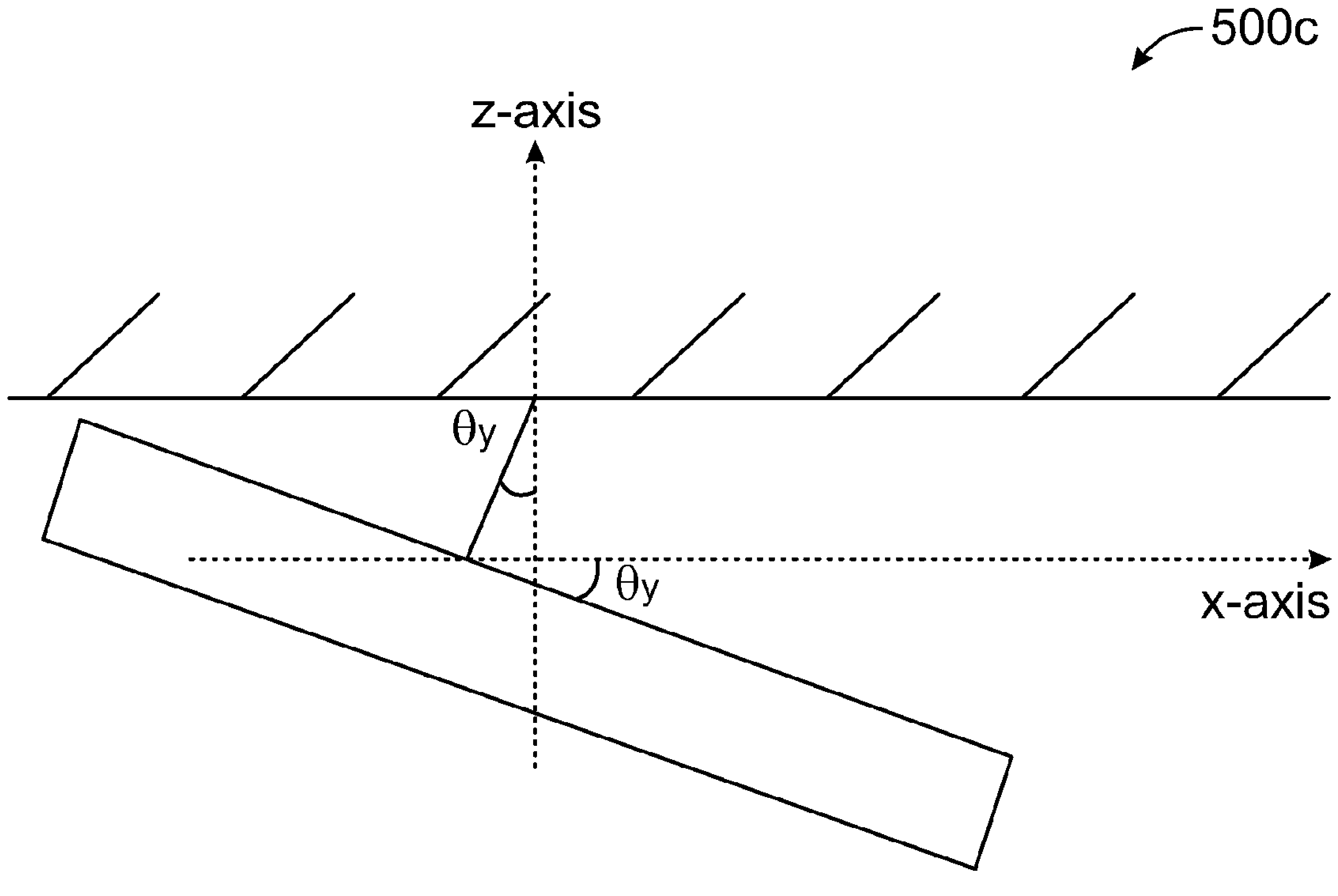

500c
z-axis
θ_y
θ_y
x-axis

FIG. 5C

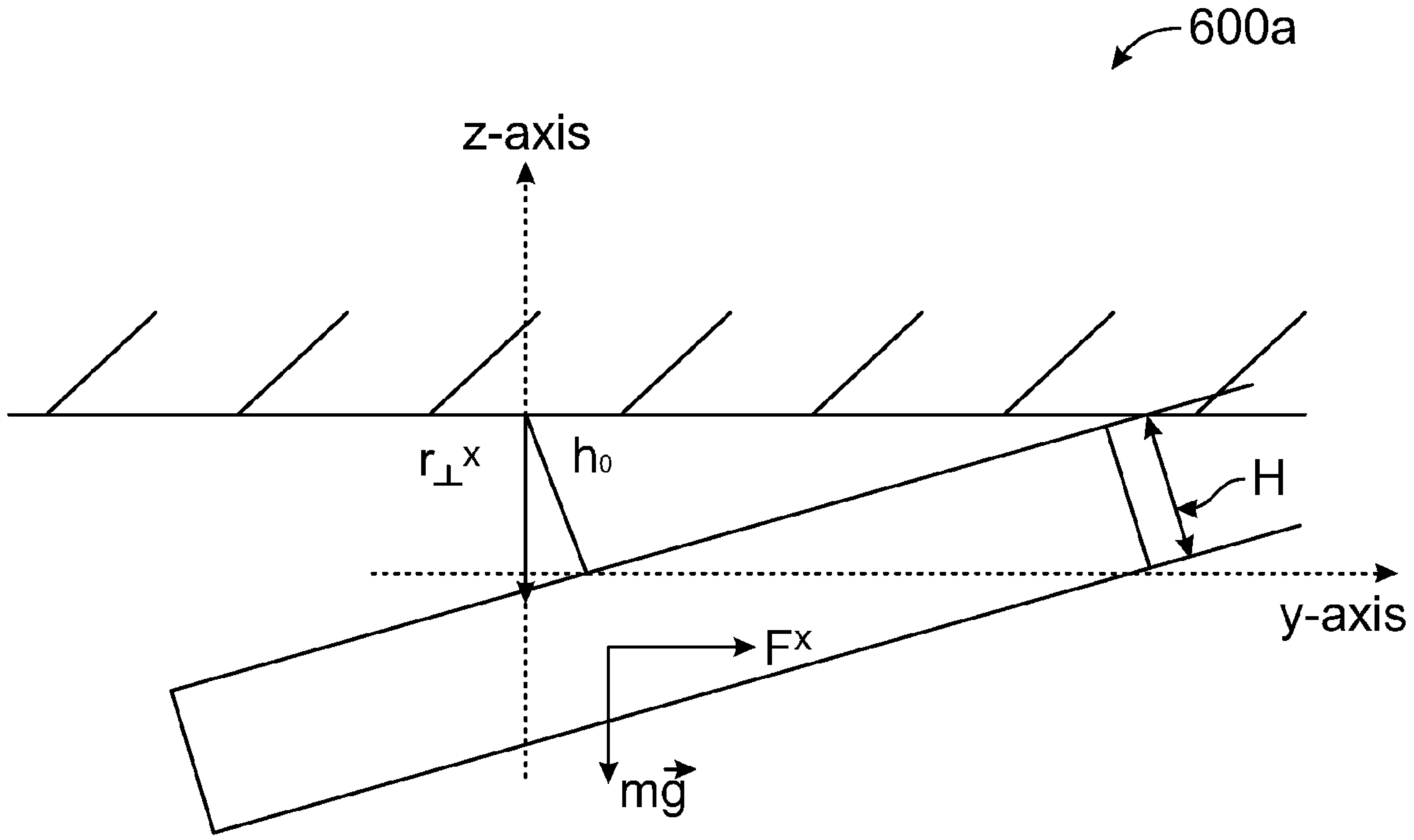

600a
z-axis
$r_{\perp}^{x}$
h_0
H
y-axis
F^x
$m\vec{g}$

FIG. 6A

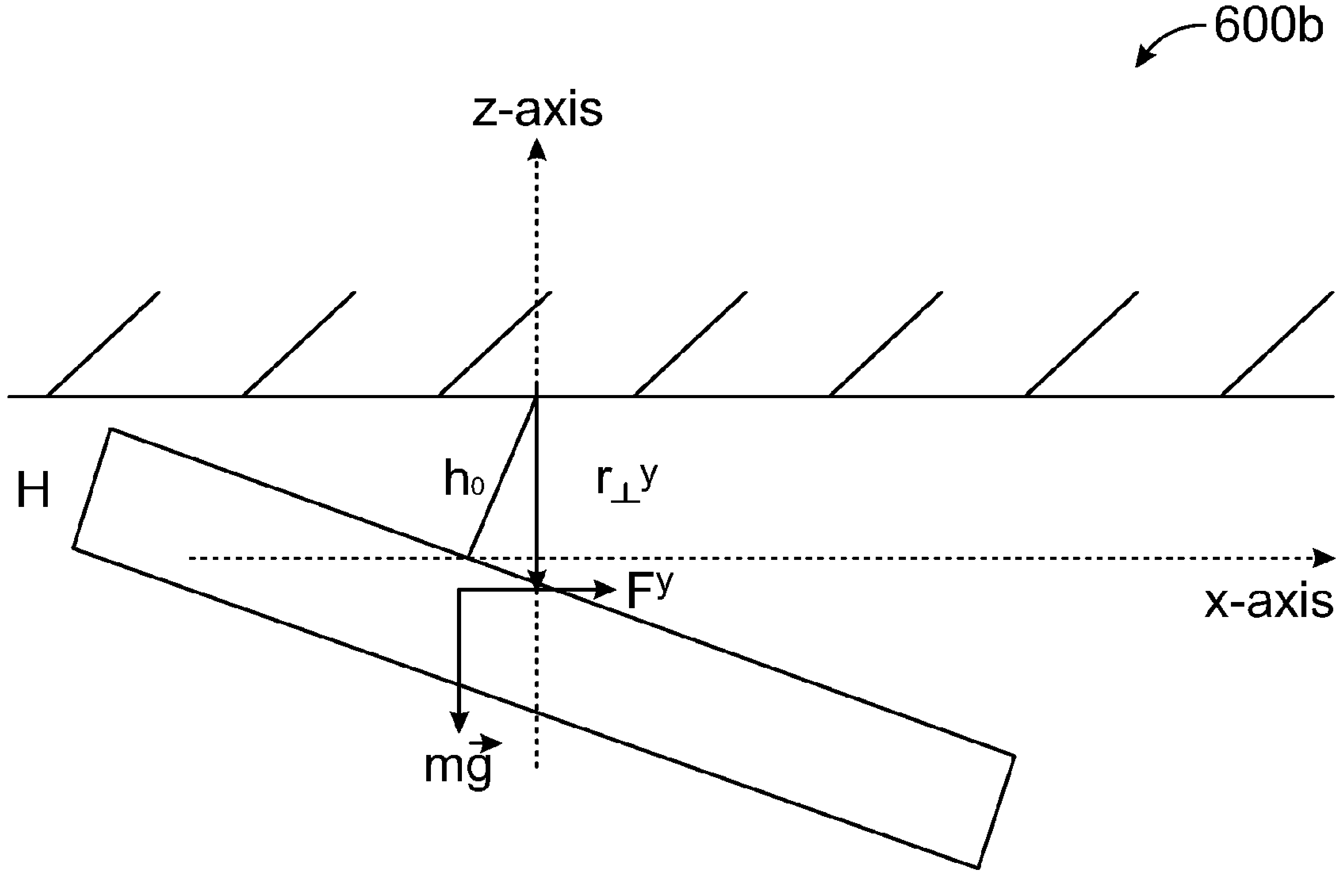

600b
z-axis
H
h_0
$r_{\perp}^{y}$
F^y
x-axis
$m\vec{g}$

FIG. 6B

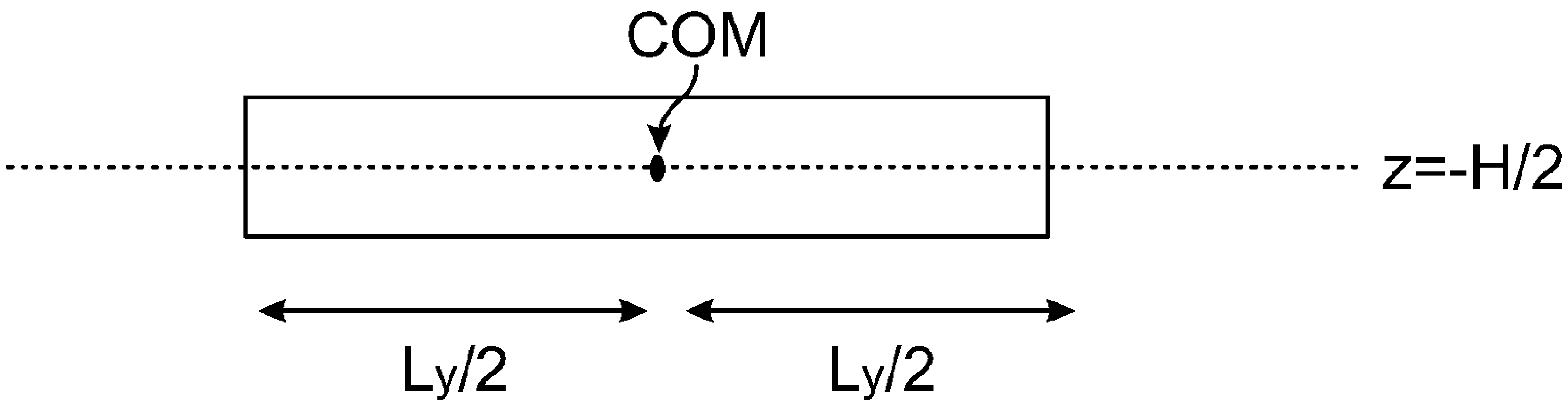


FIG. 7

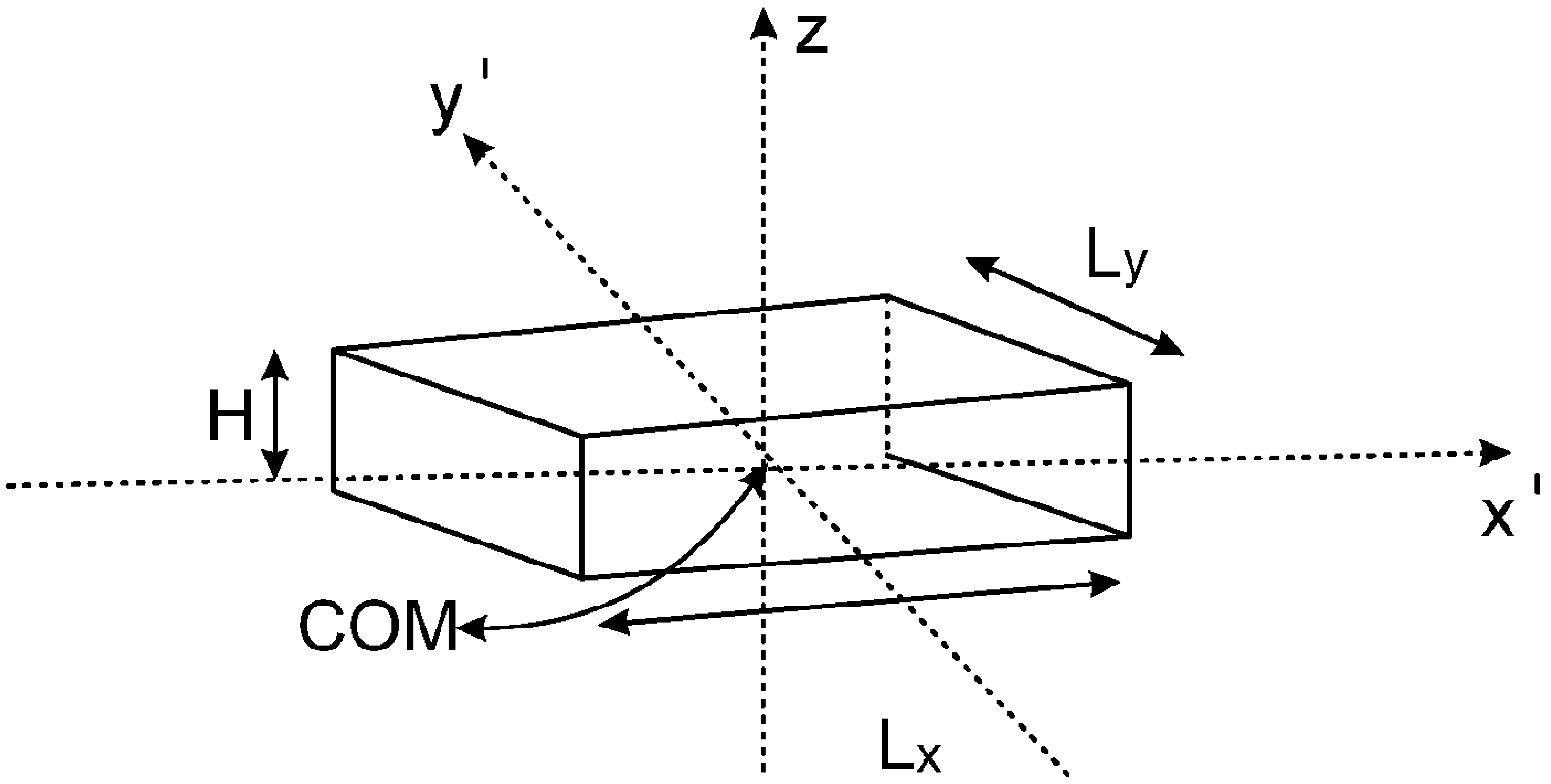


FIG. 8

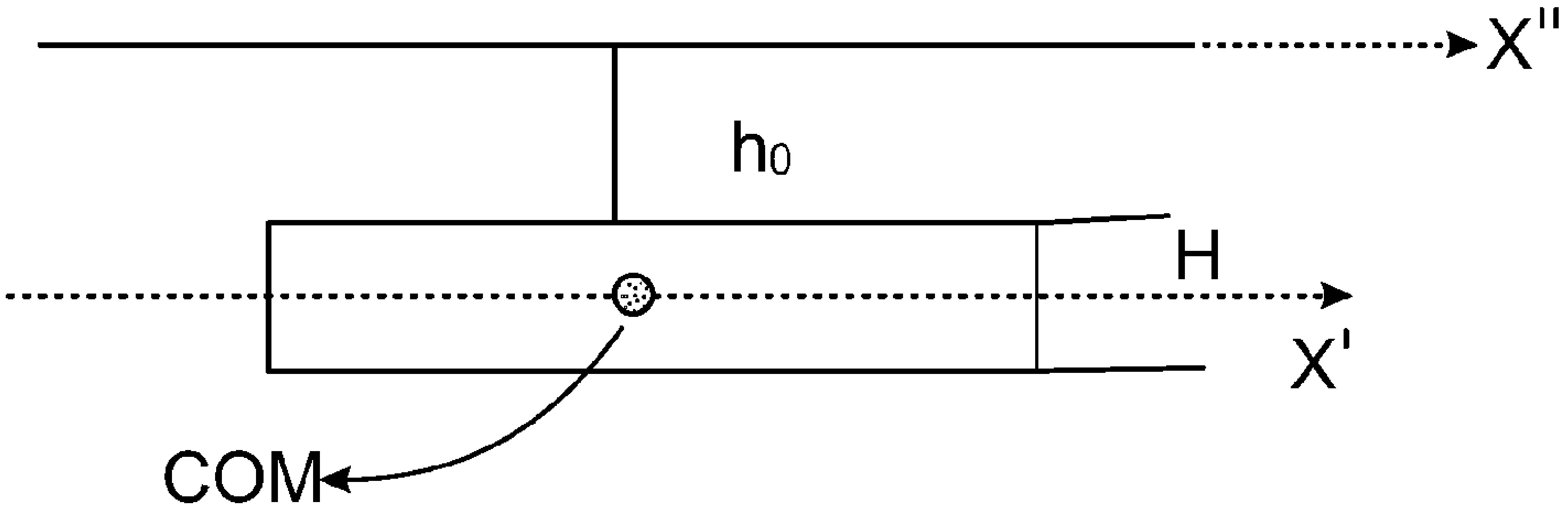


FIG. 9

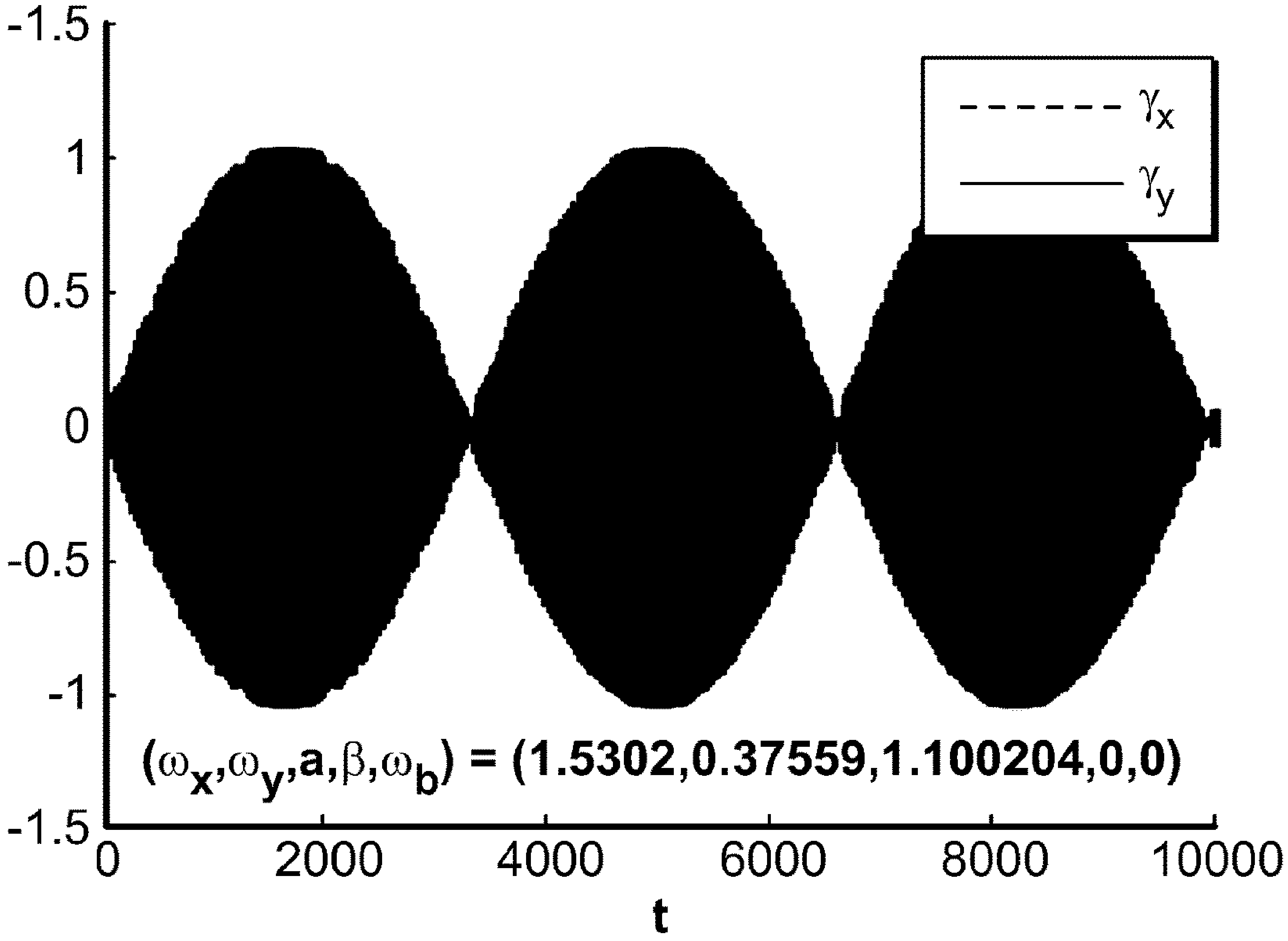


FIG. 10A

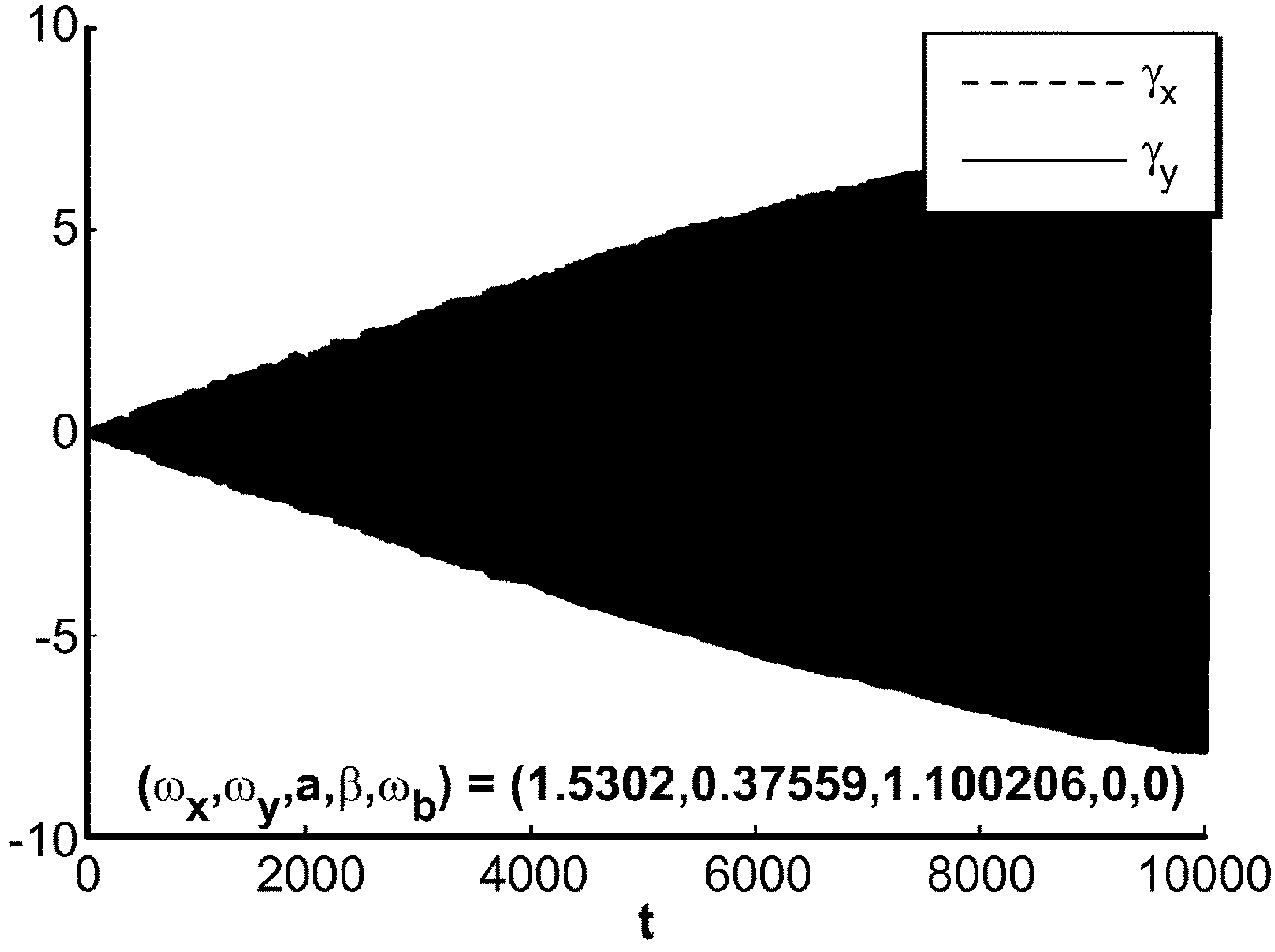


FIG. 10B

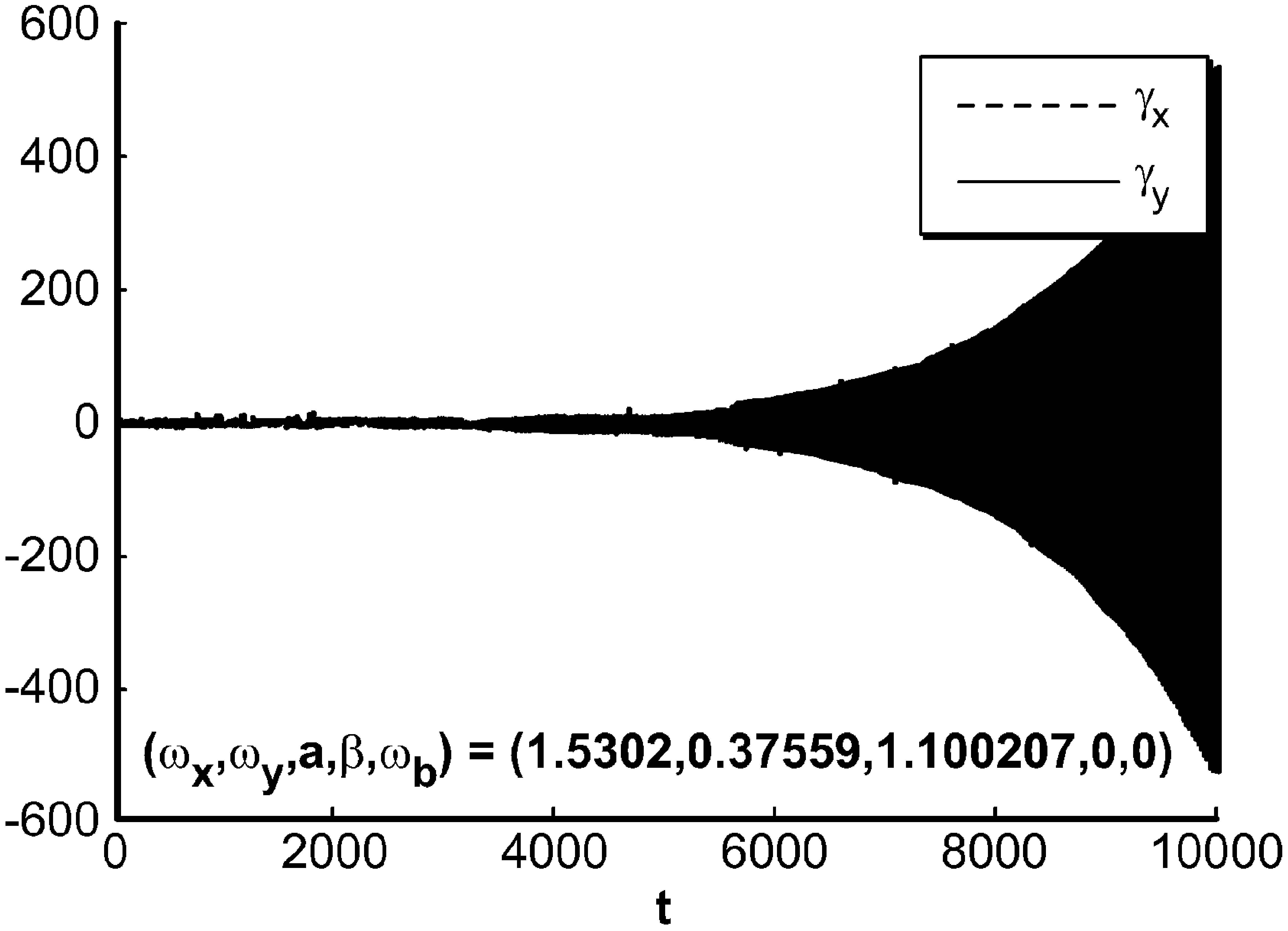


FIG. 10C

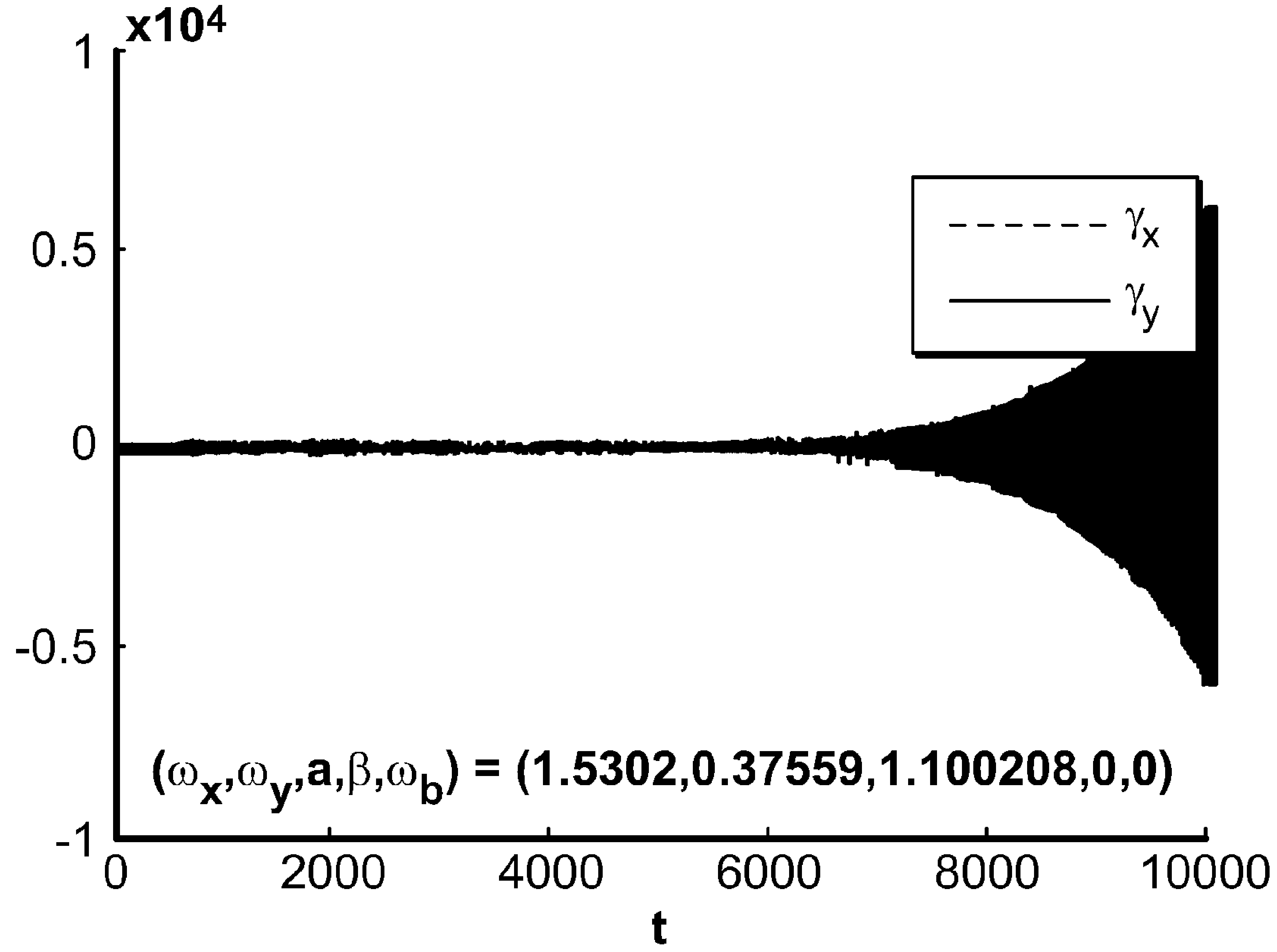


FIG. 10D

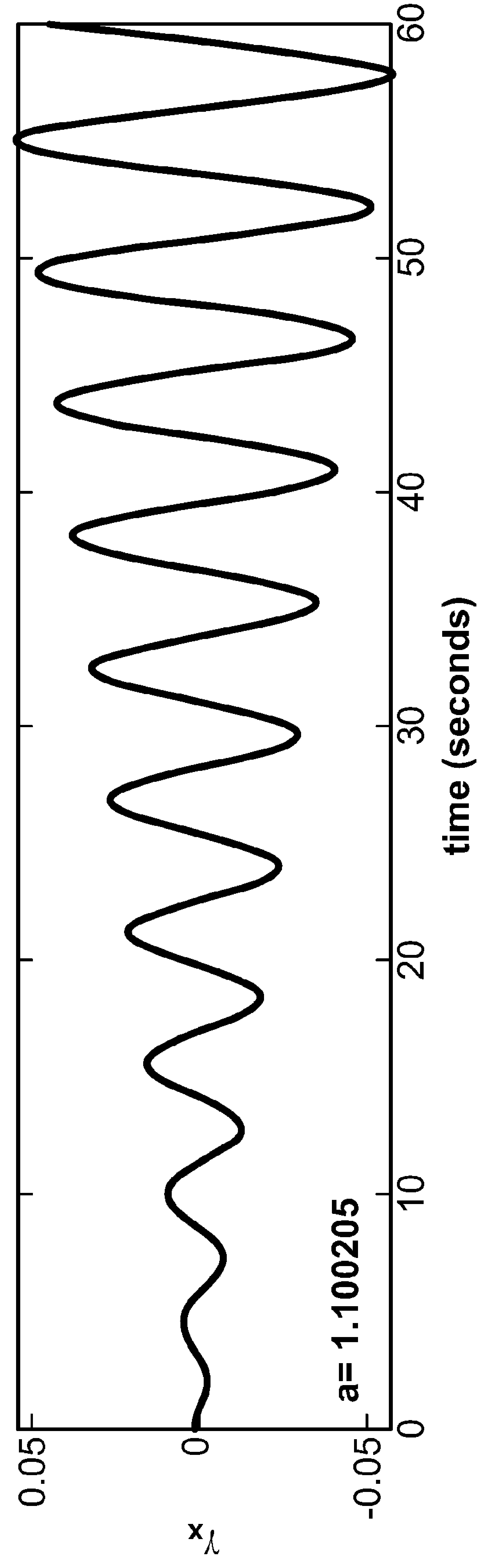


FIG. 11A

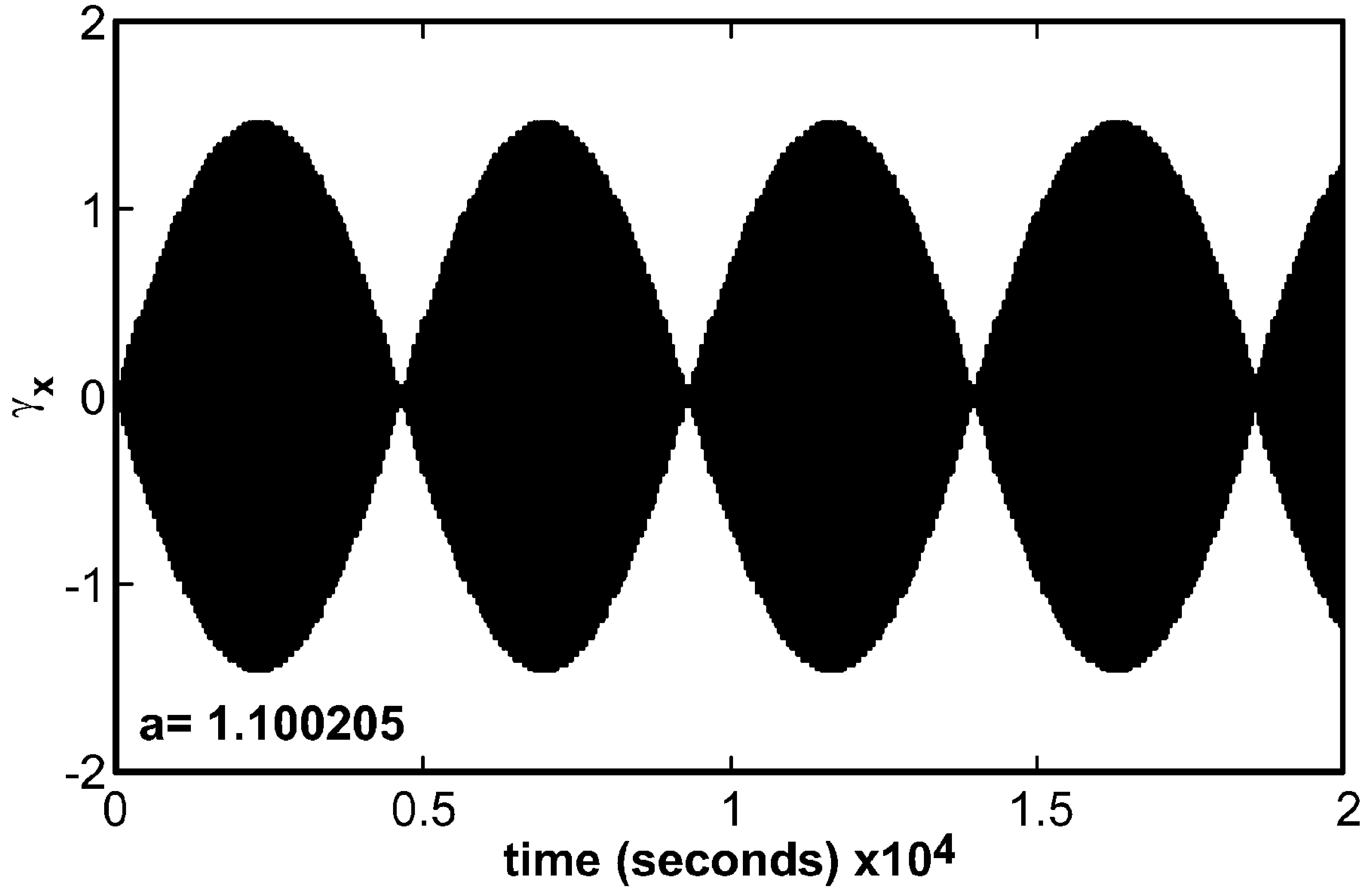


FIG. 11B

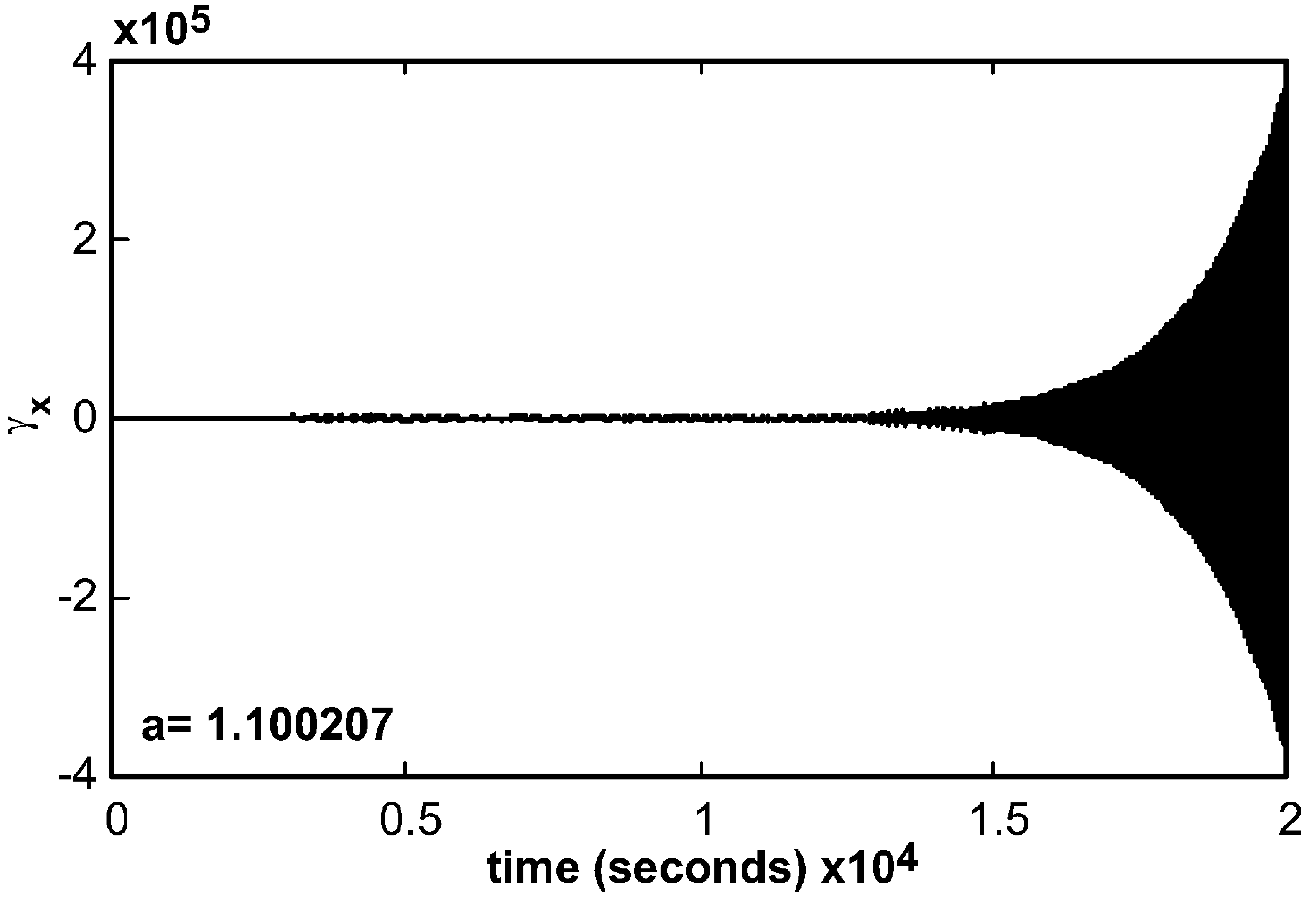


FIG. 11C

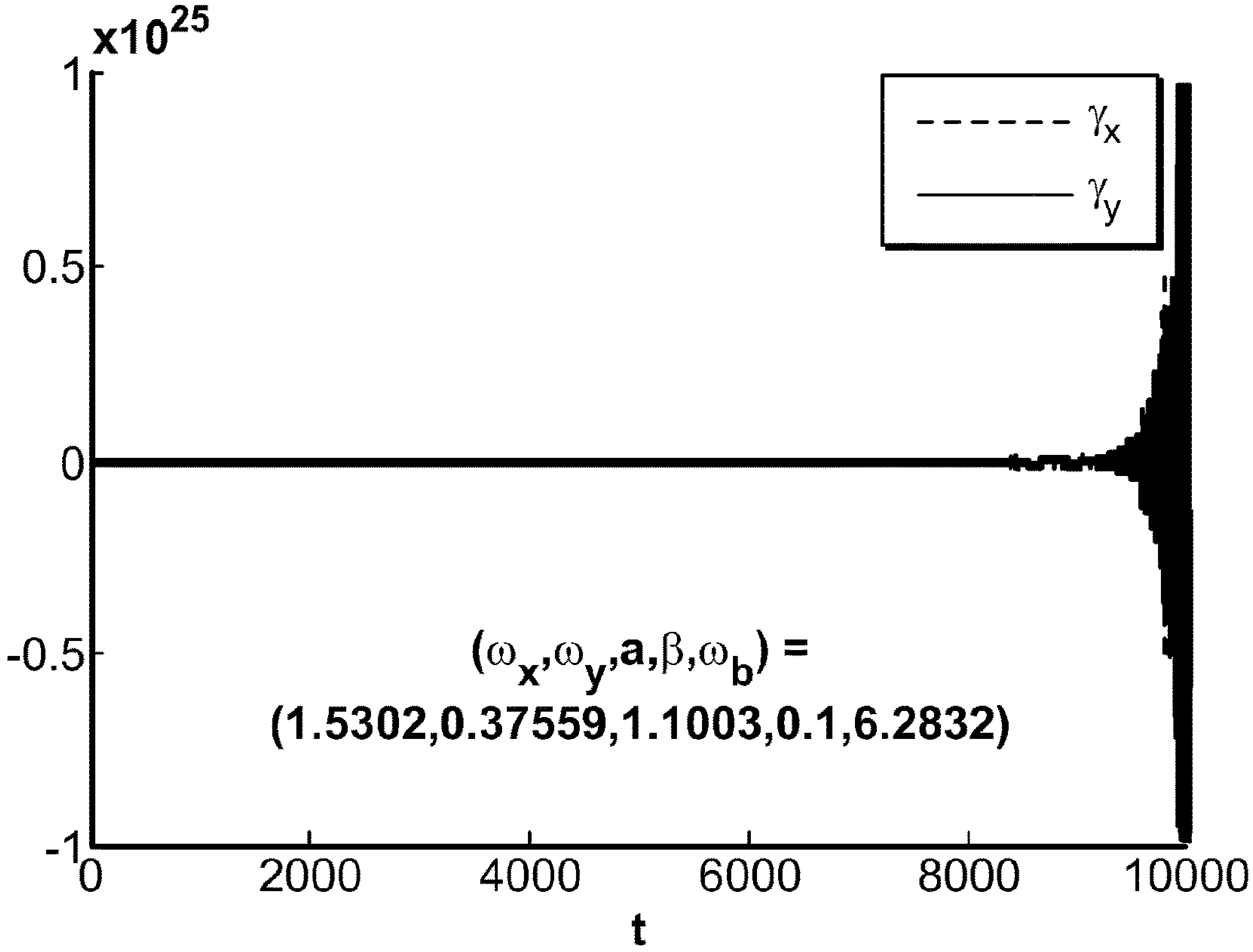


FIG. 12A

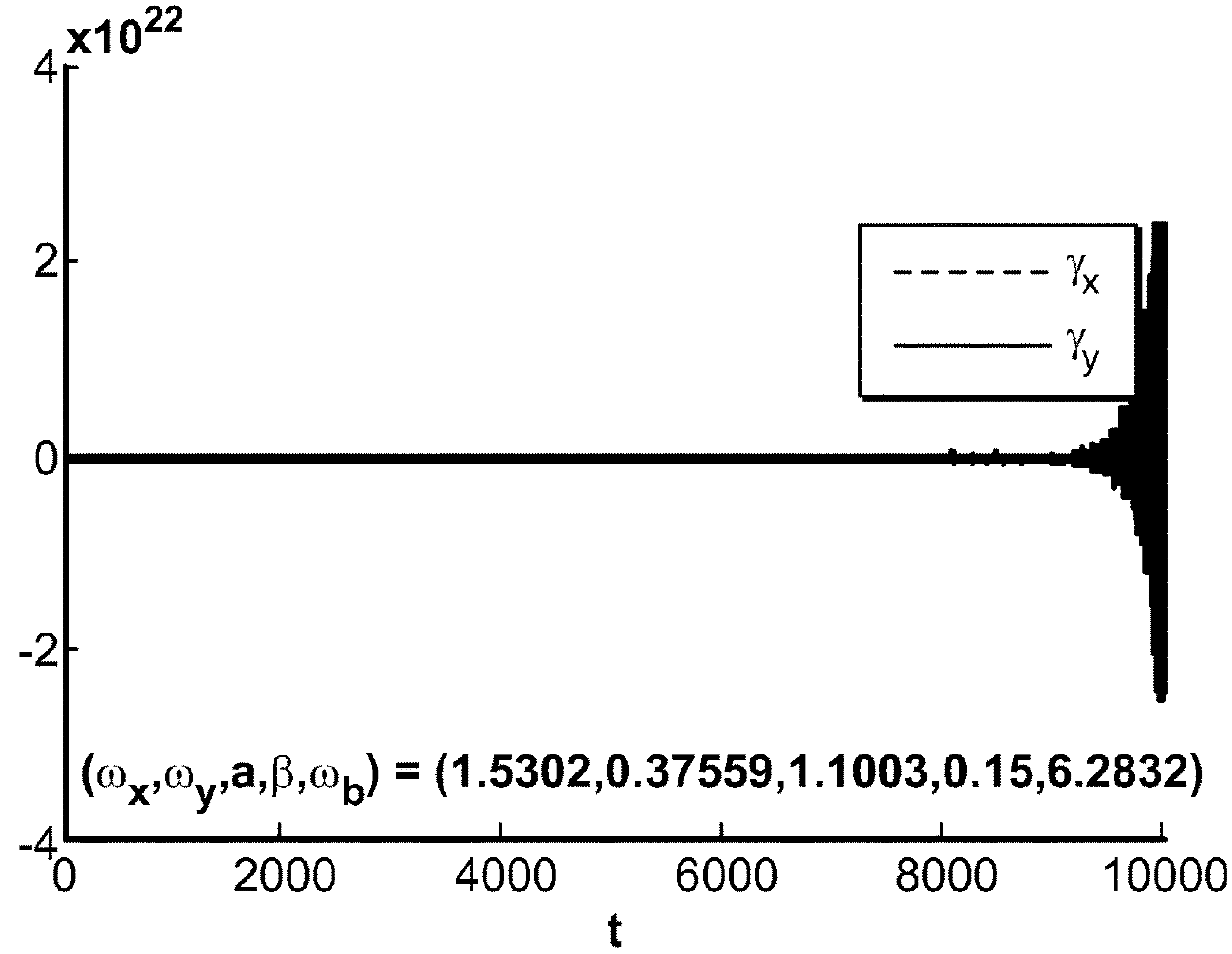


FIG. 12B

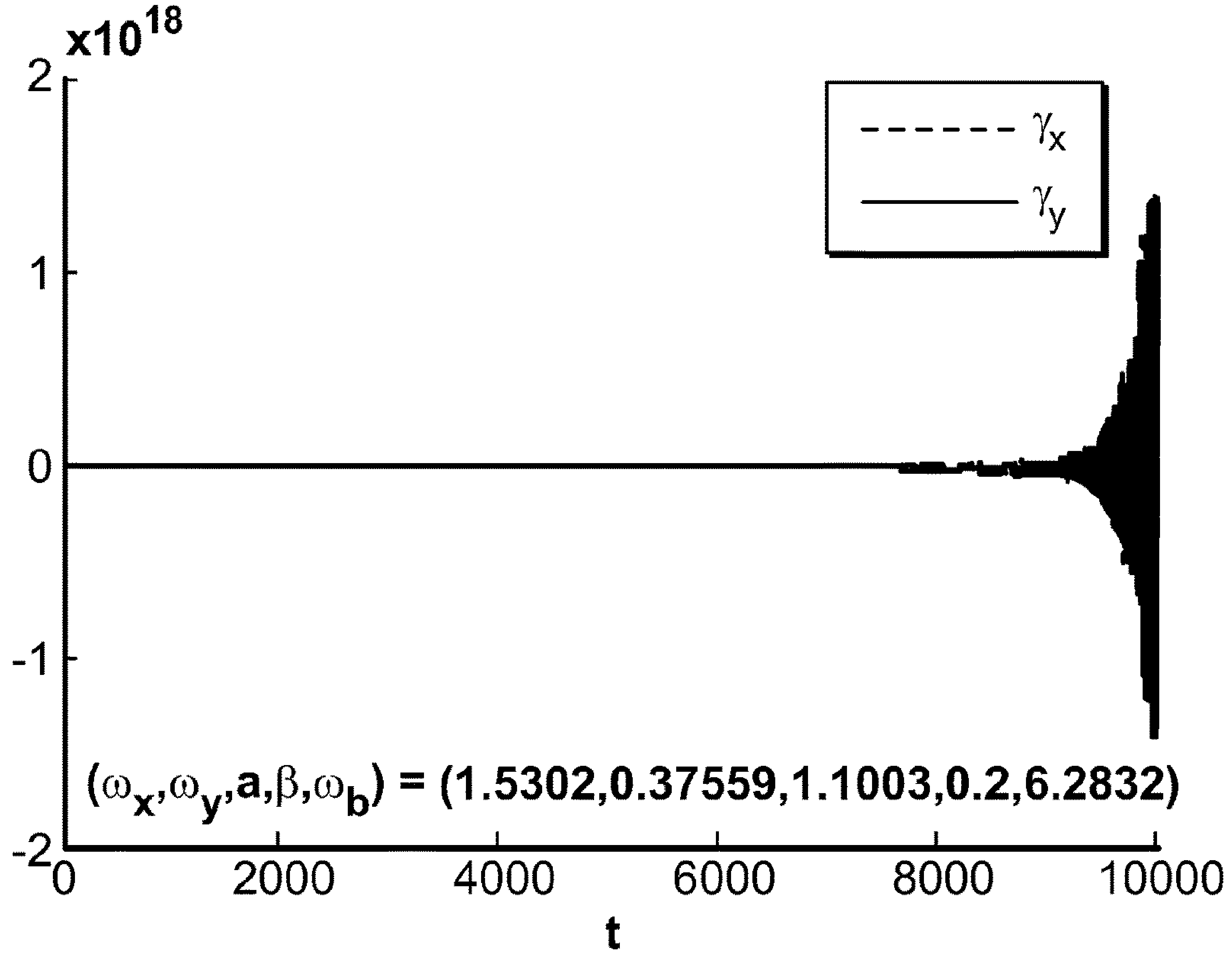


FIG. 12C

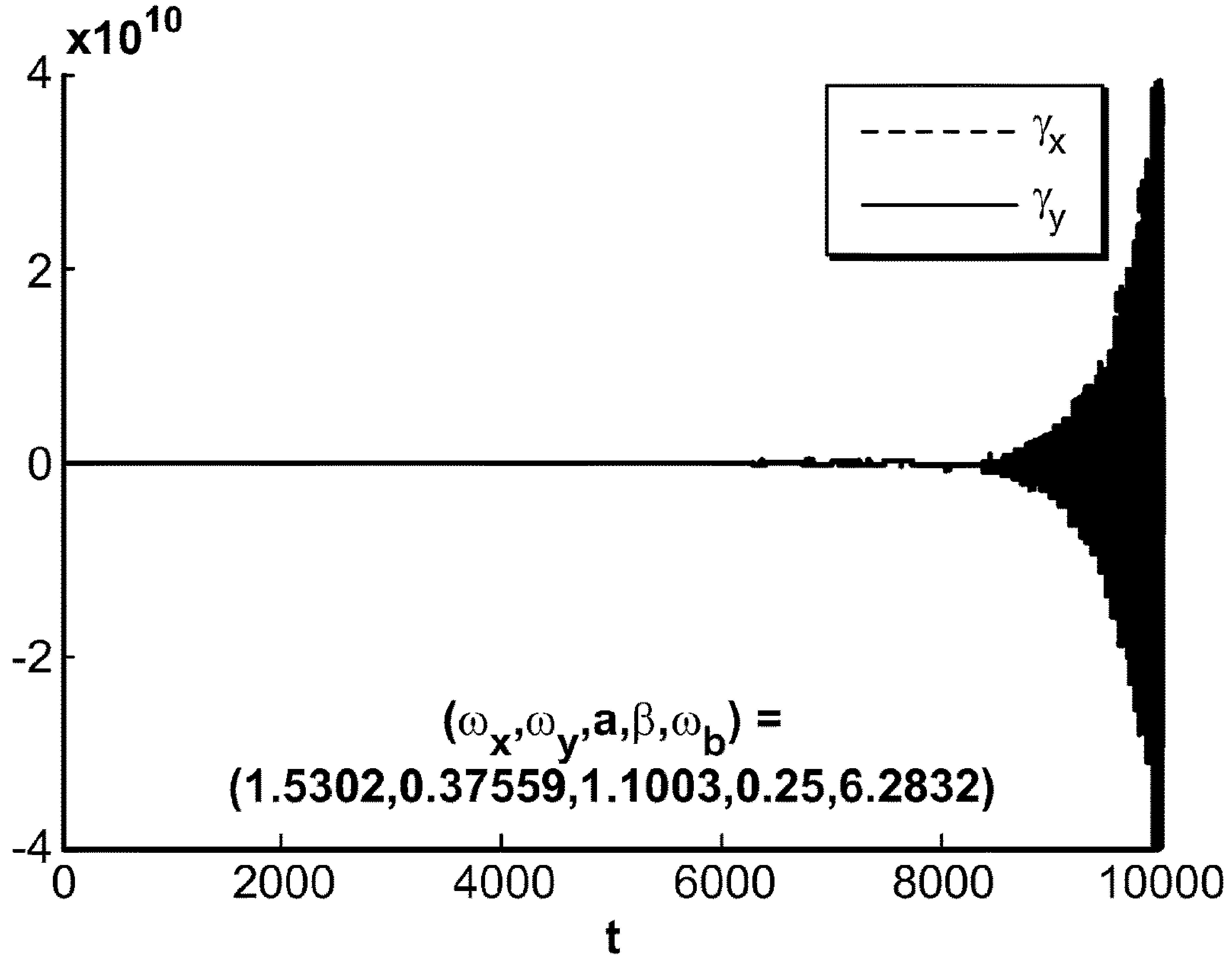


FIG. 12D

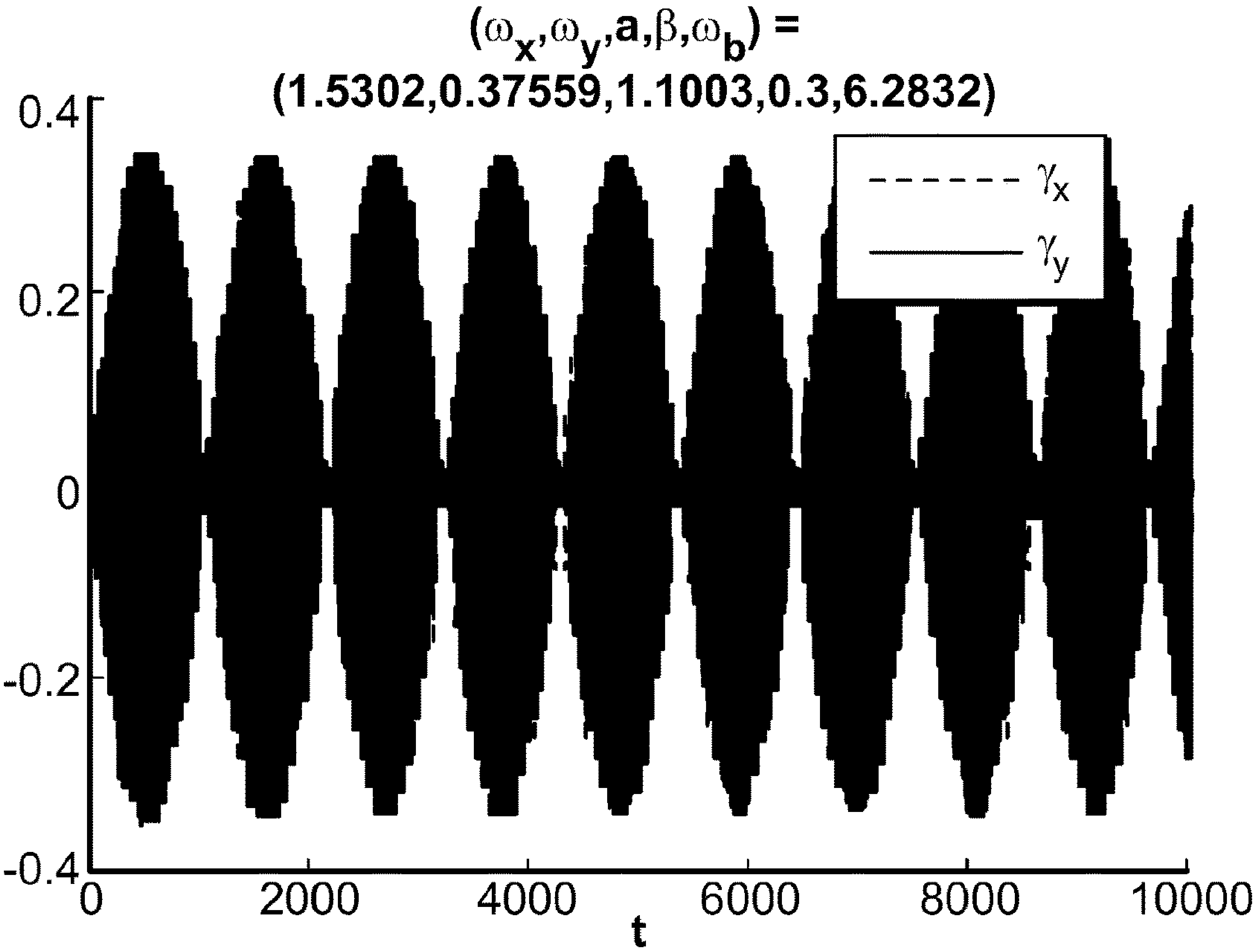


FIG. 12E

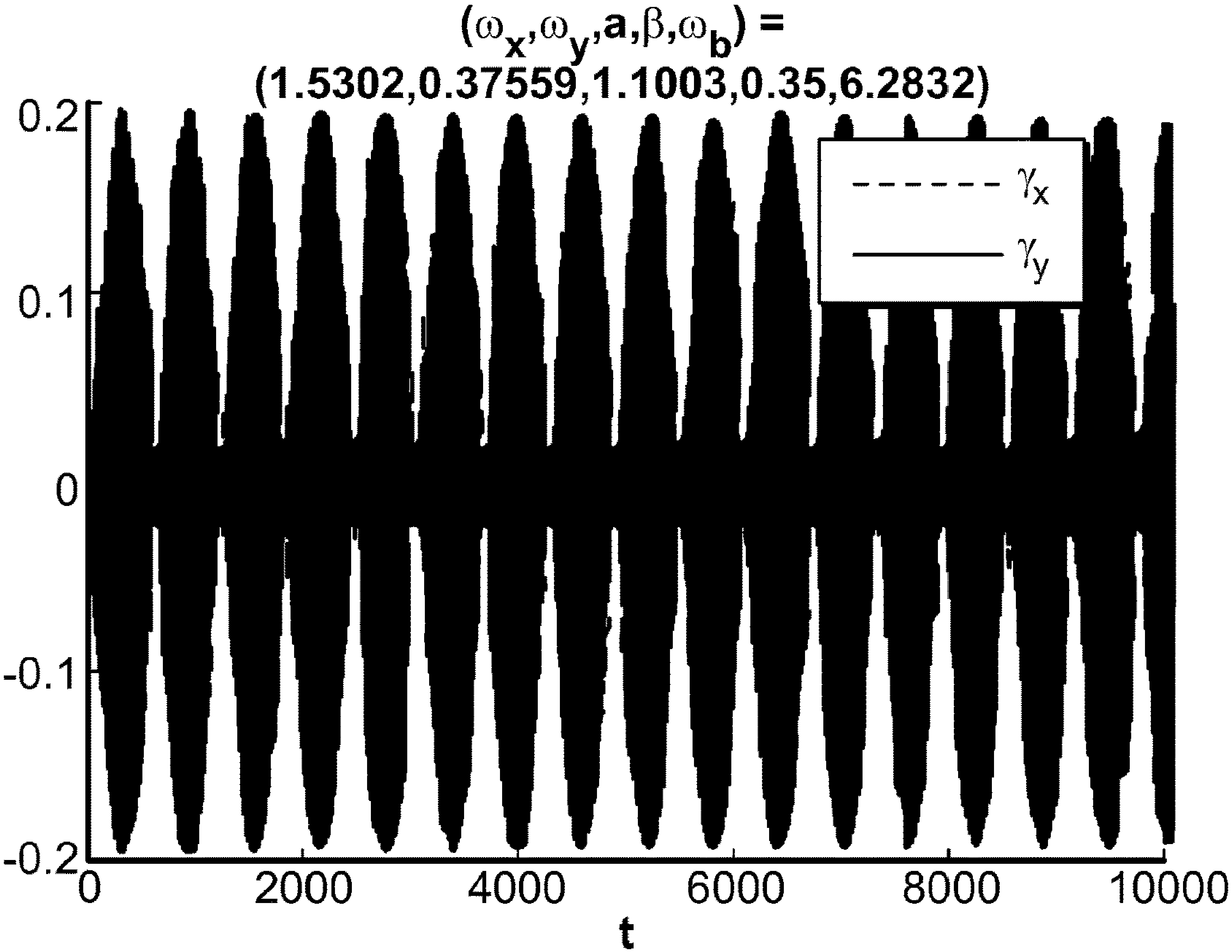


FIG. 12F

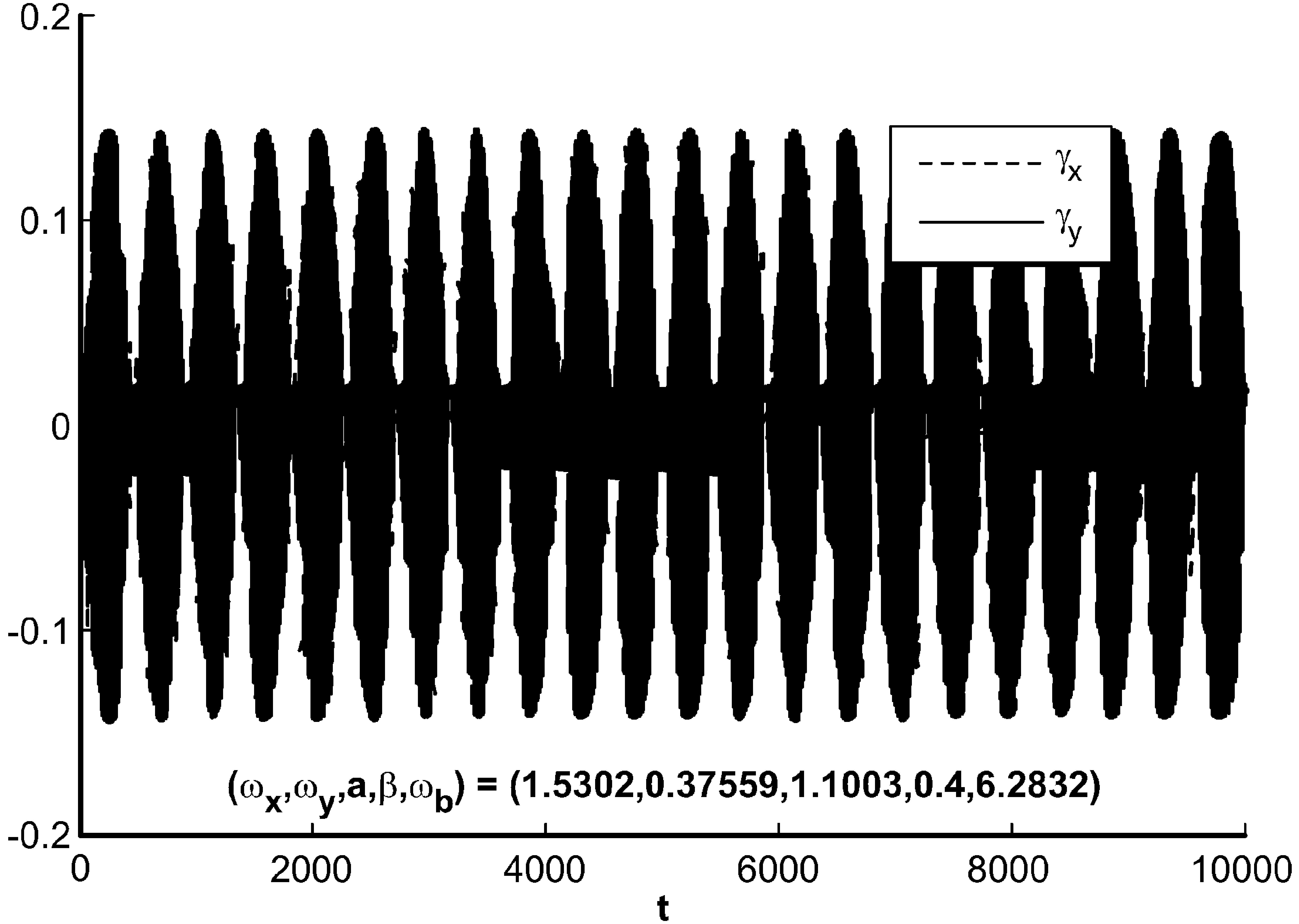

0.2
0.1
0
-0.1
-0.2
0
2000
4000
6000
8000
10000
t
γ_x
γ_y
$(\omega_x,\omega_y,a,\beta,\omega_b) = (1.5302,0.37559,1.1003,0.4,6.2832)$

FIG. 12G

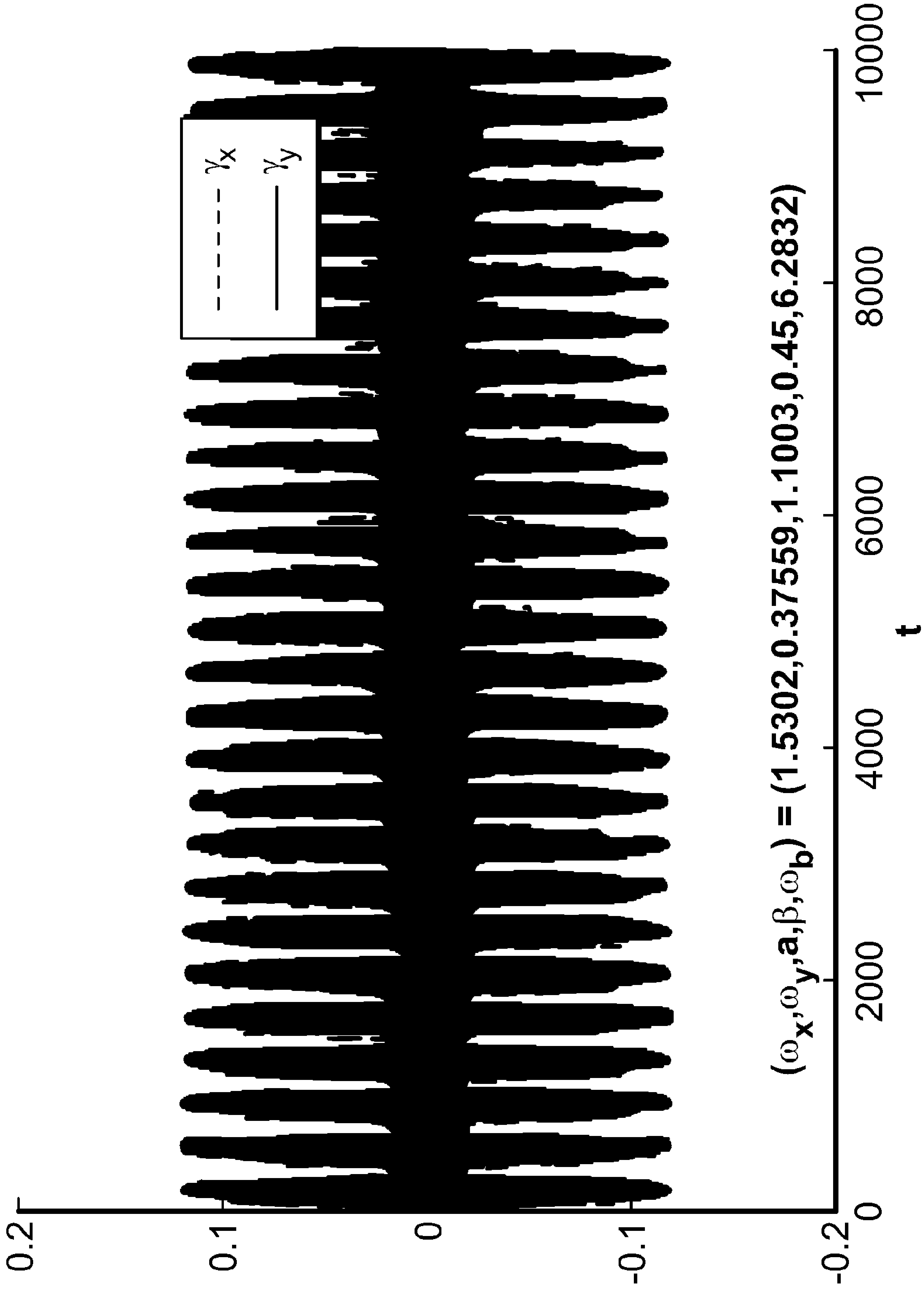
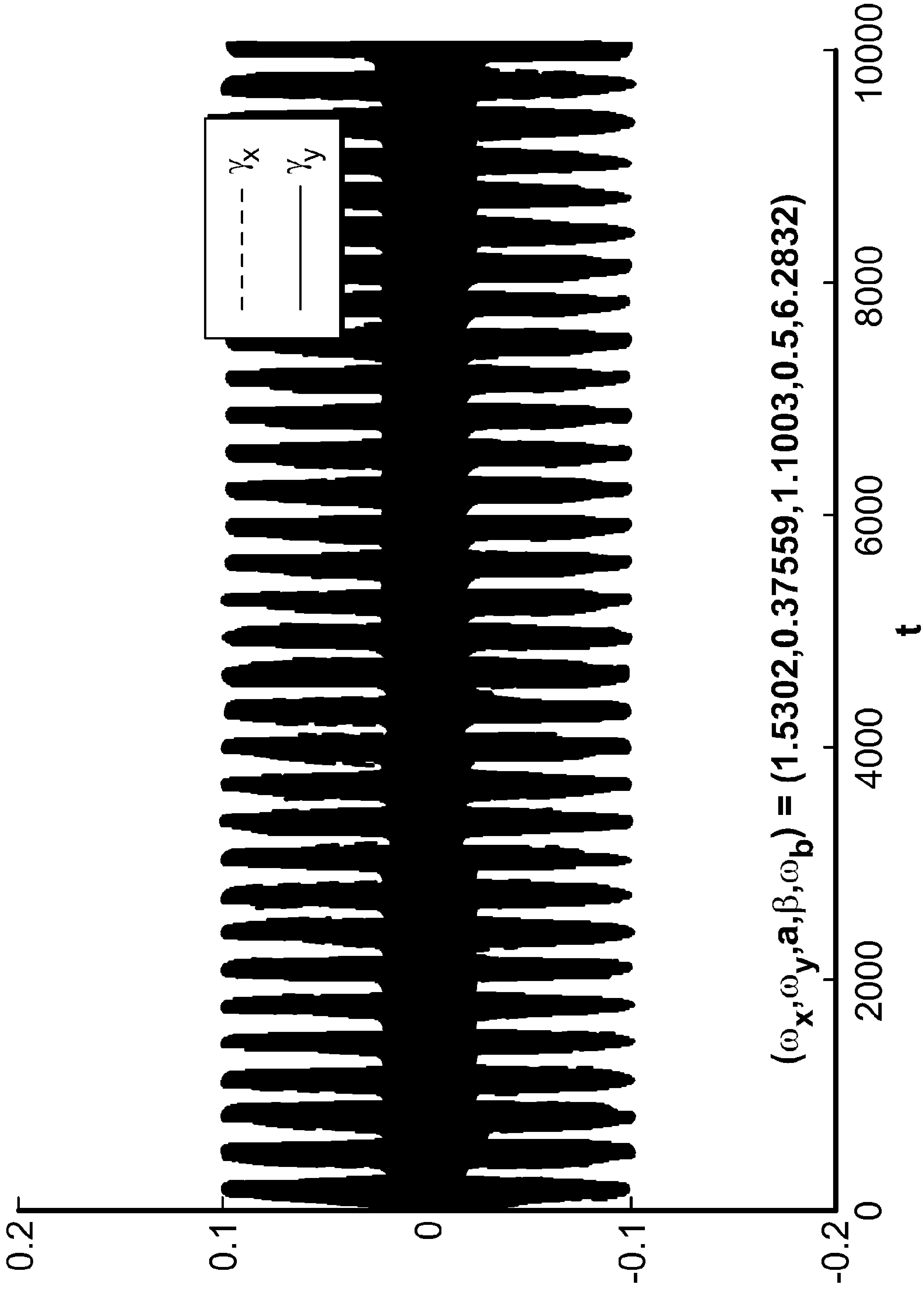

0.2
0.1
0
-0.1
-0.2
0
2000
4000
6000
8000
10000
t
γ_x
γ_y
$(\omega_x,\omega_y,a,\beta,\omega_b) = (1.5302,0.37559,1.1003,0.45,6.2832)$

FIG. 12H



$(\omega_x,\omega_y,a,\beta,\omega_b) = (1.5302,0.37559,1.1003,0.5,6.2832)$

FIG. 12I

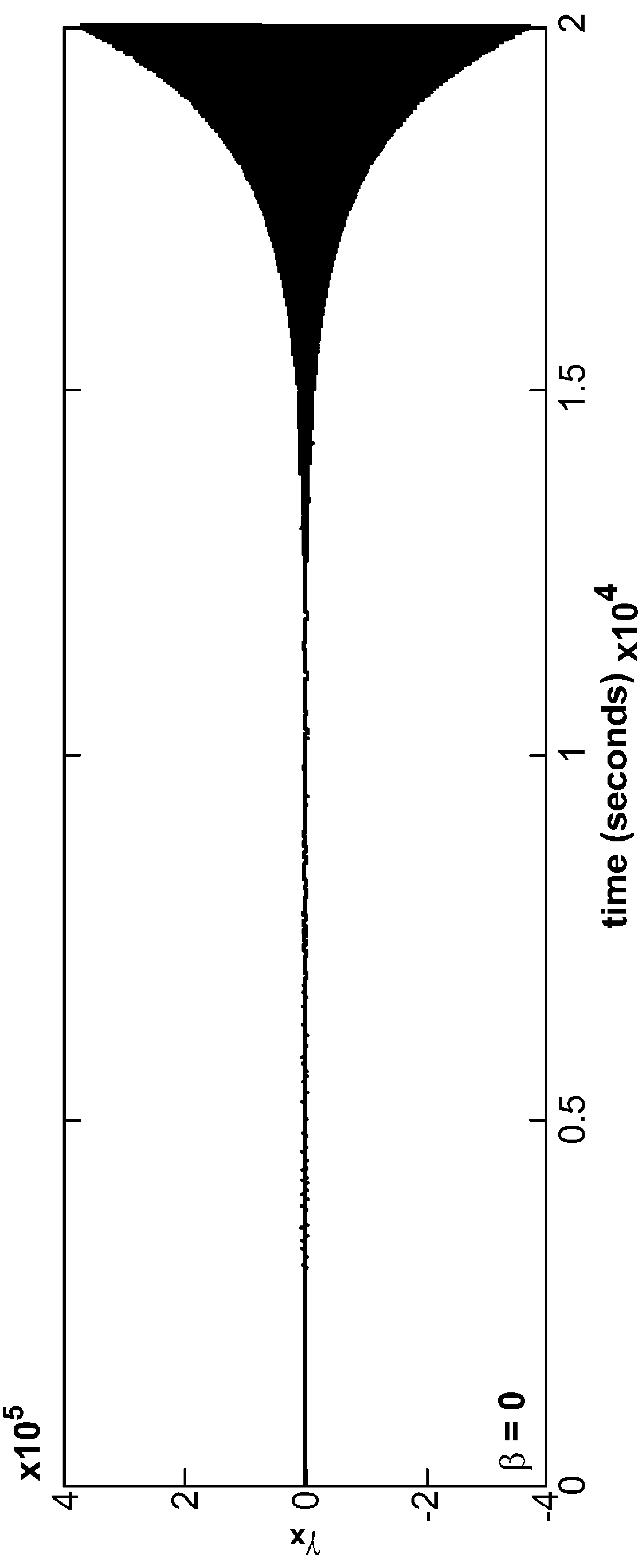


FIG. 13A

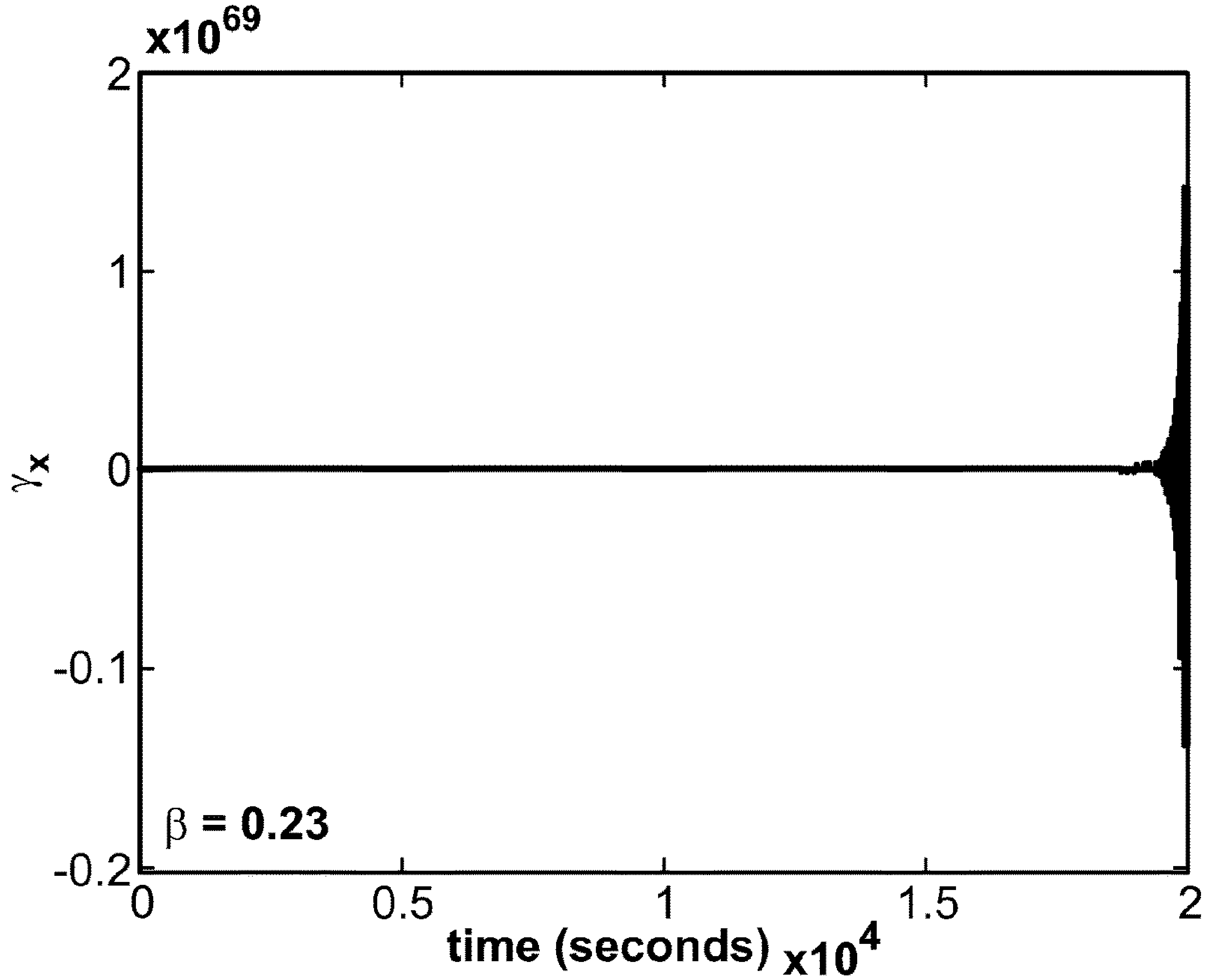


FIG. 13B

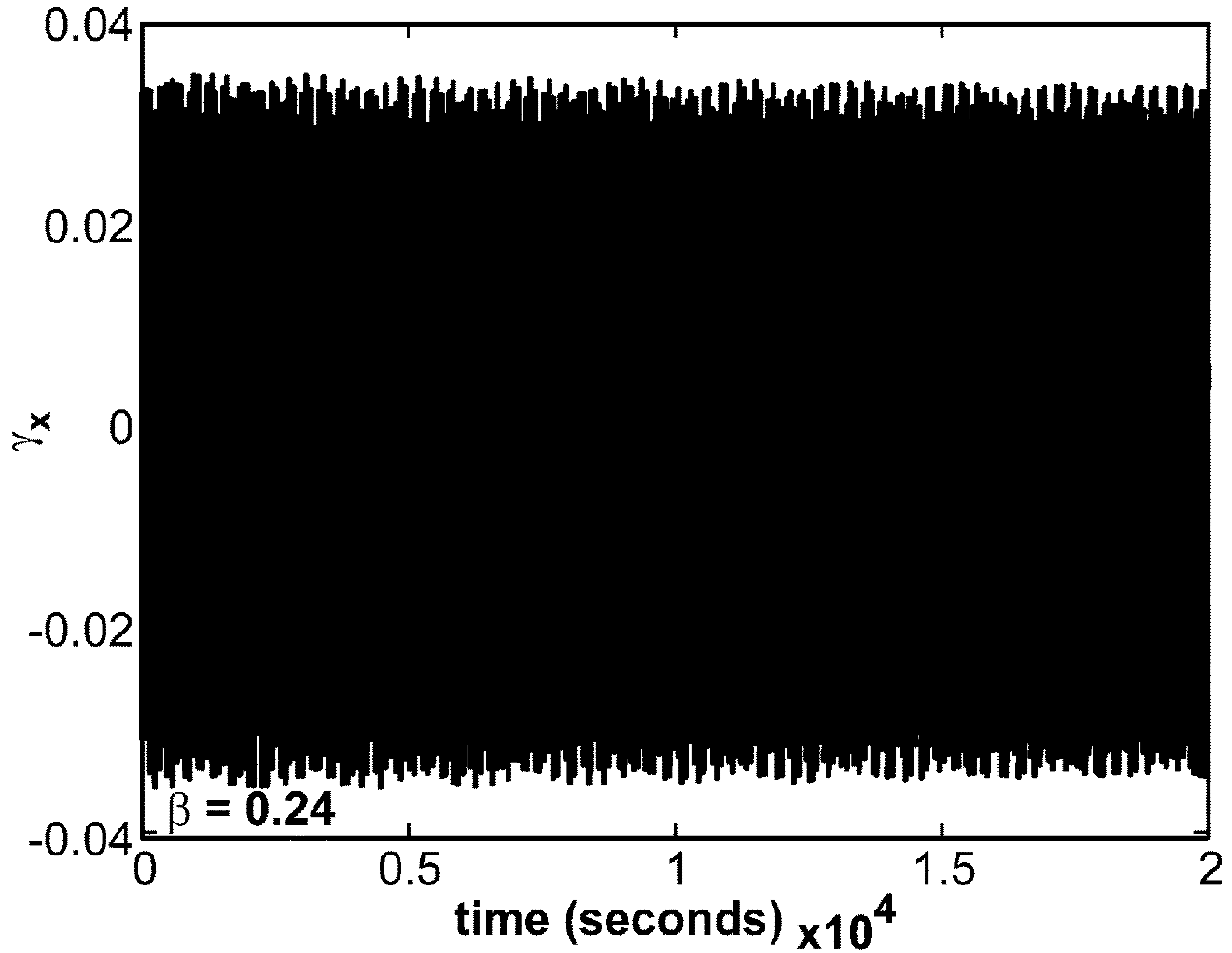


FIG. 13C

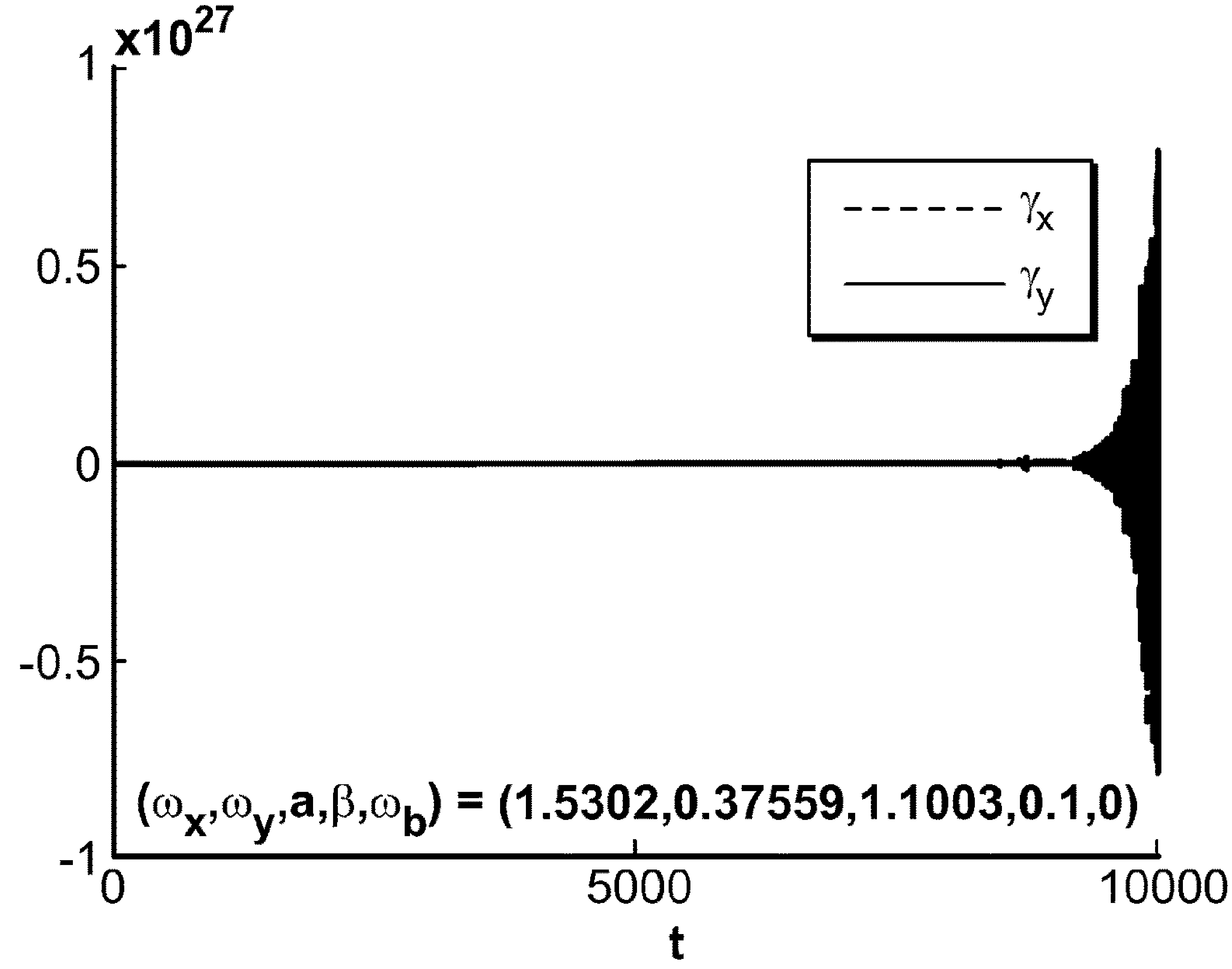


FIG. 14A

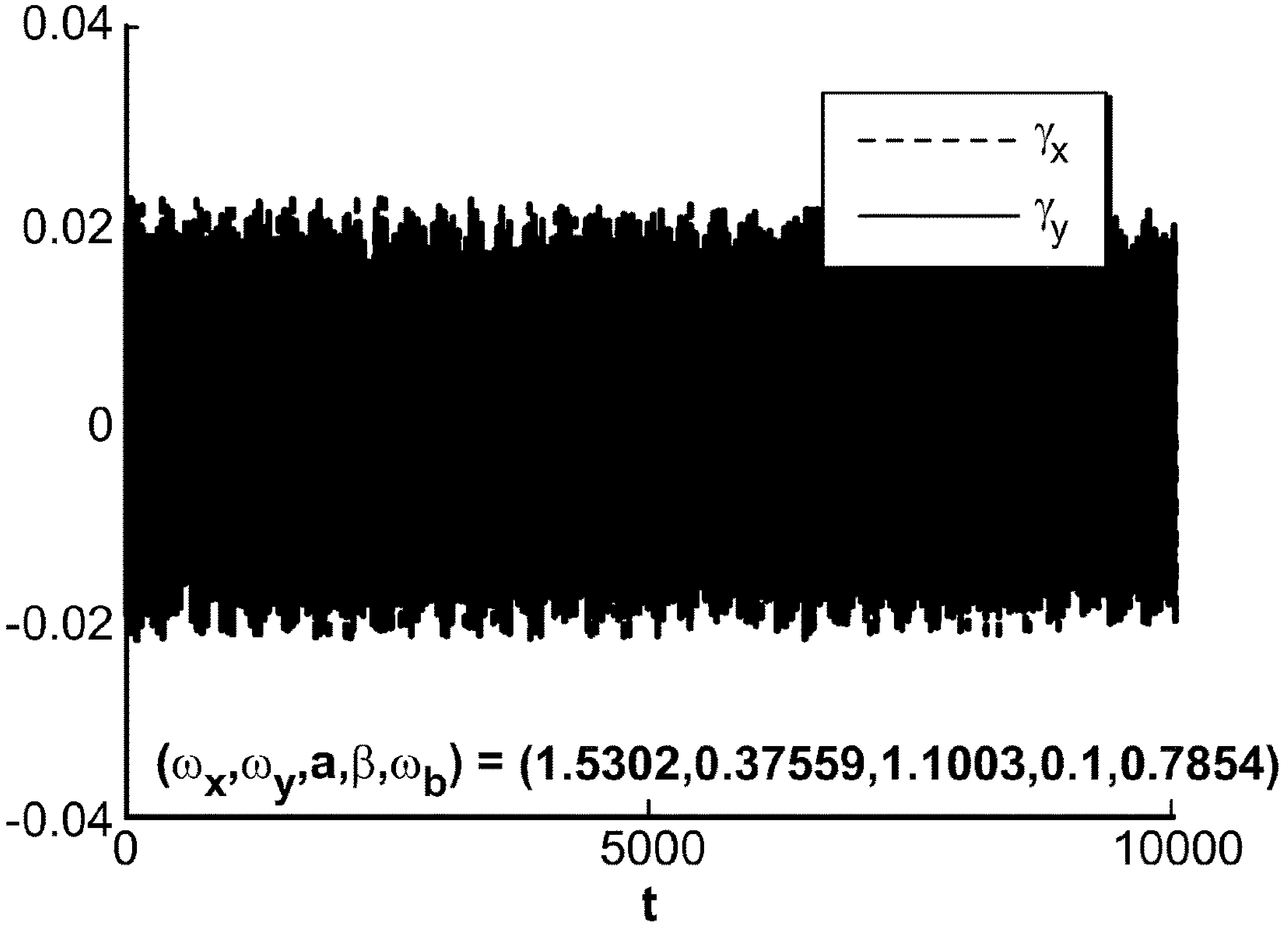


FIG. 14B

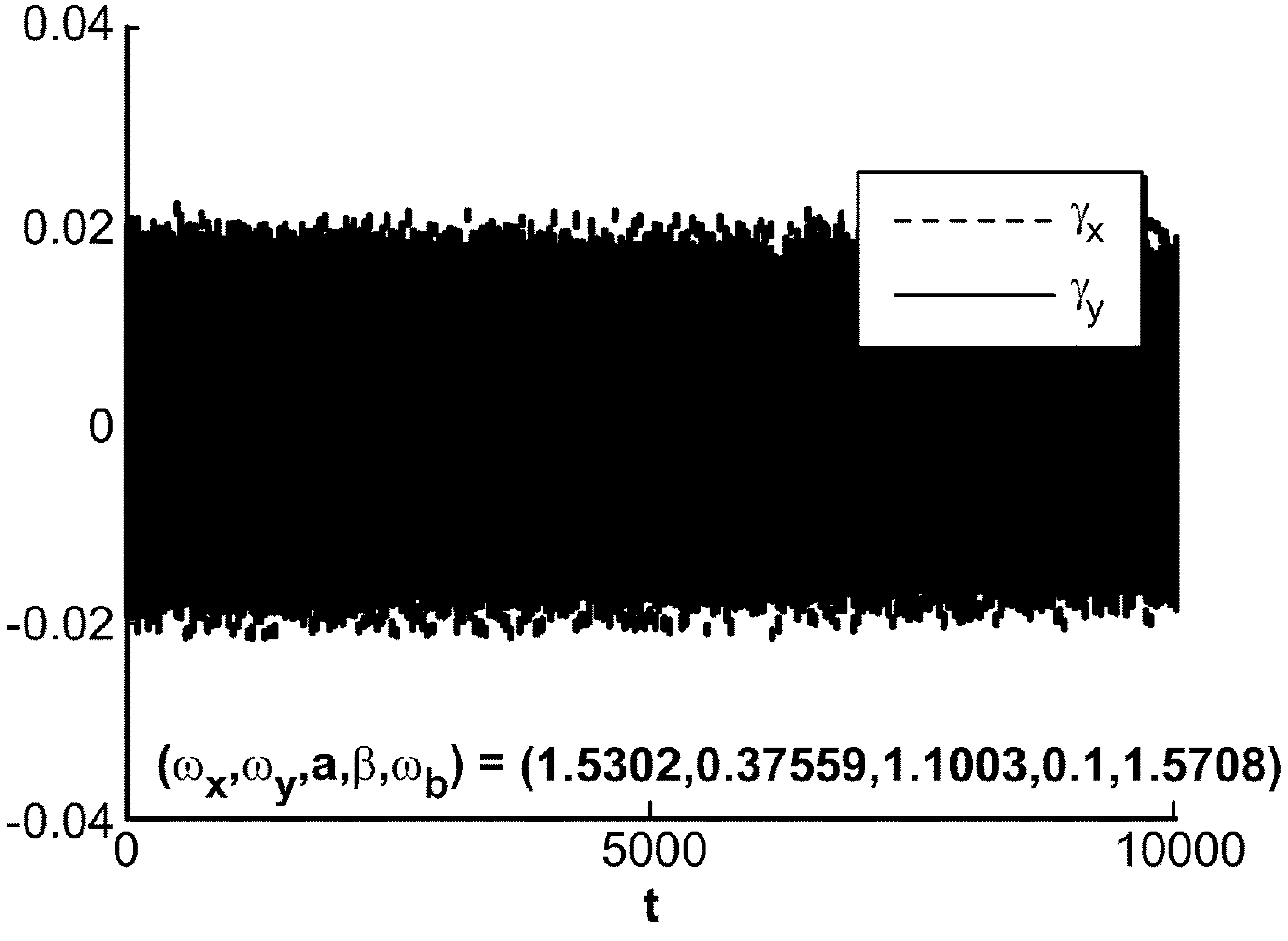


FIG. 14C

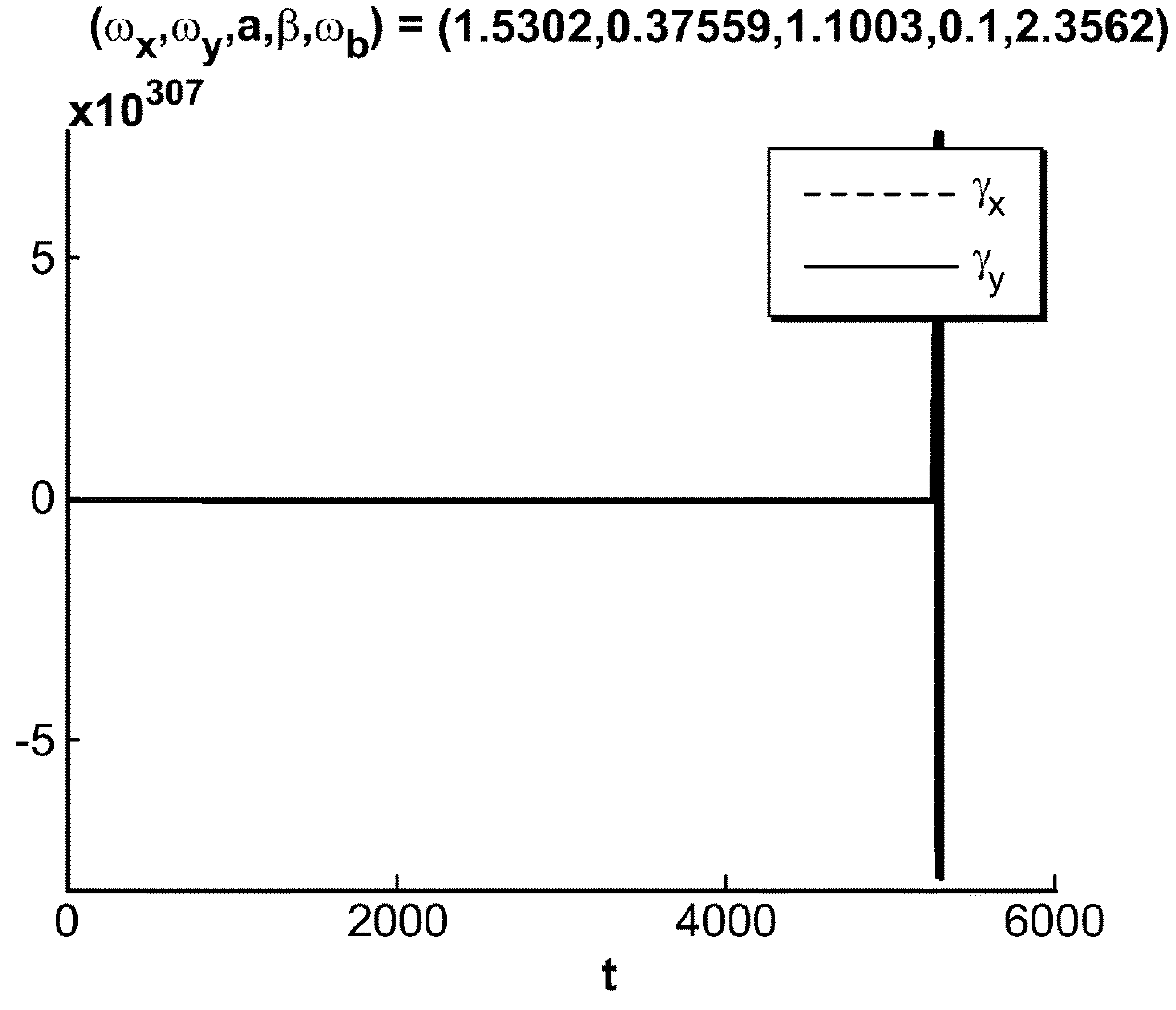


FIG. 14D

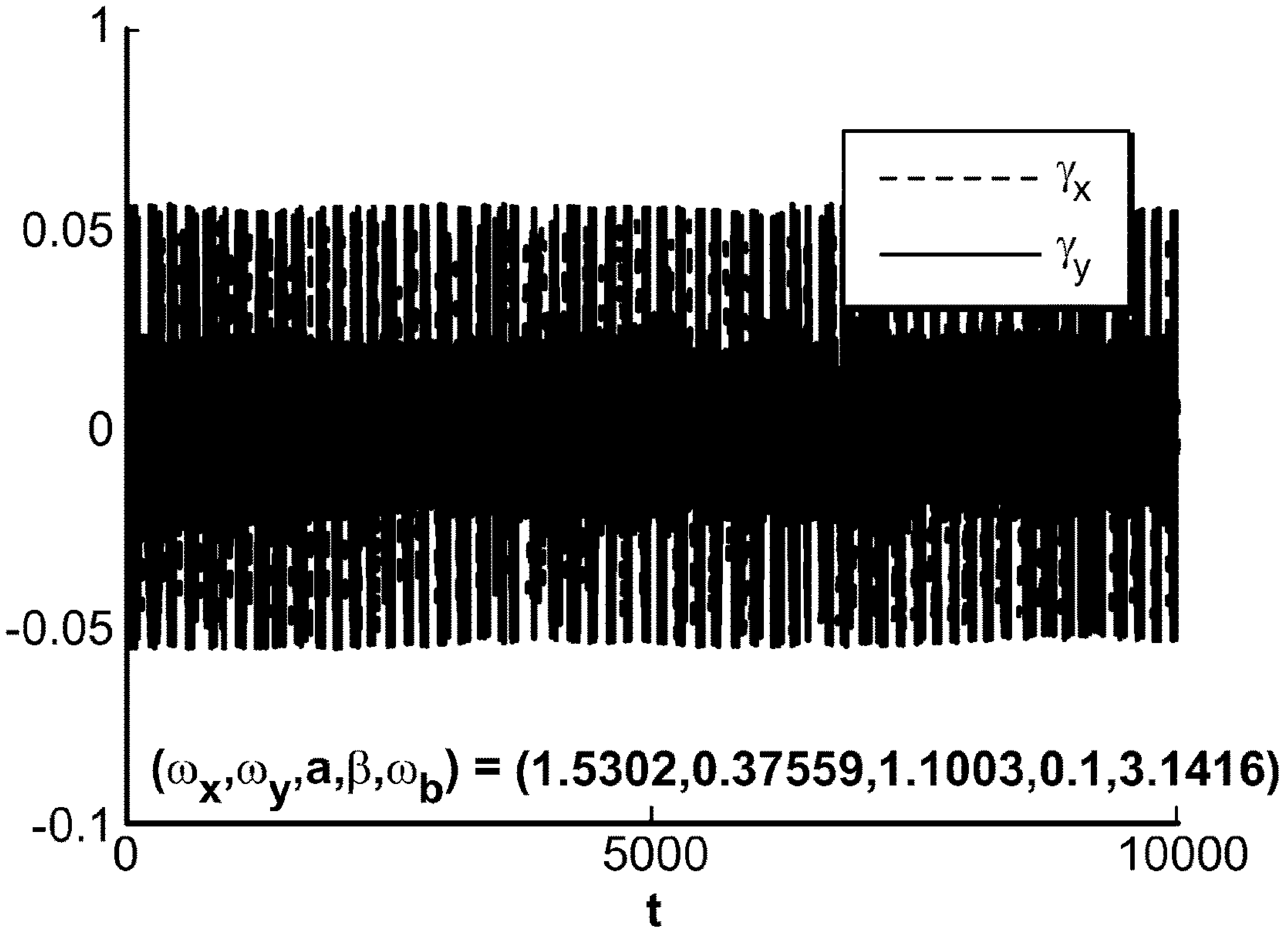


FIG. 14E

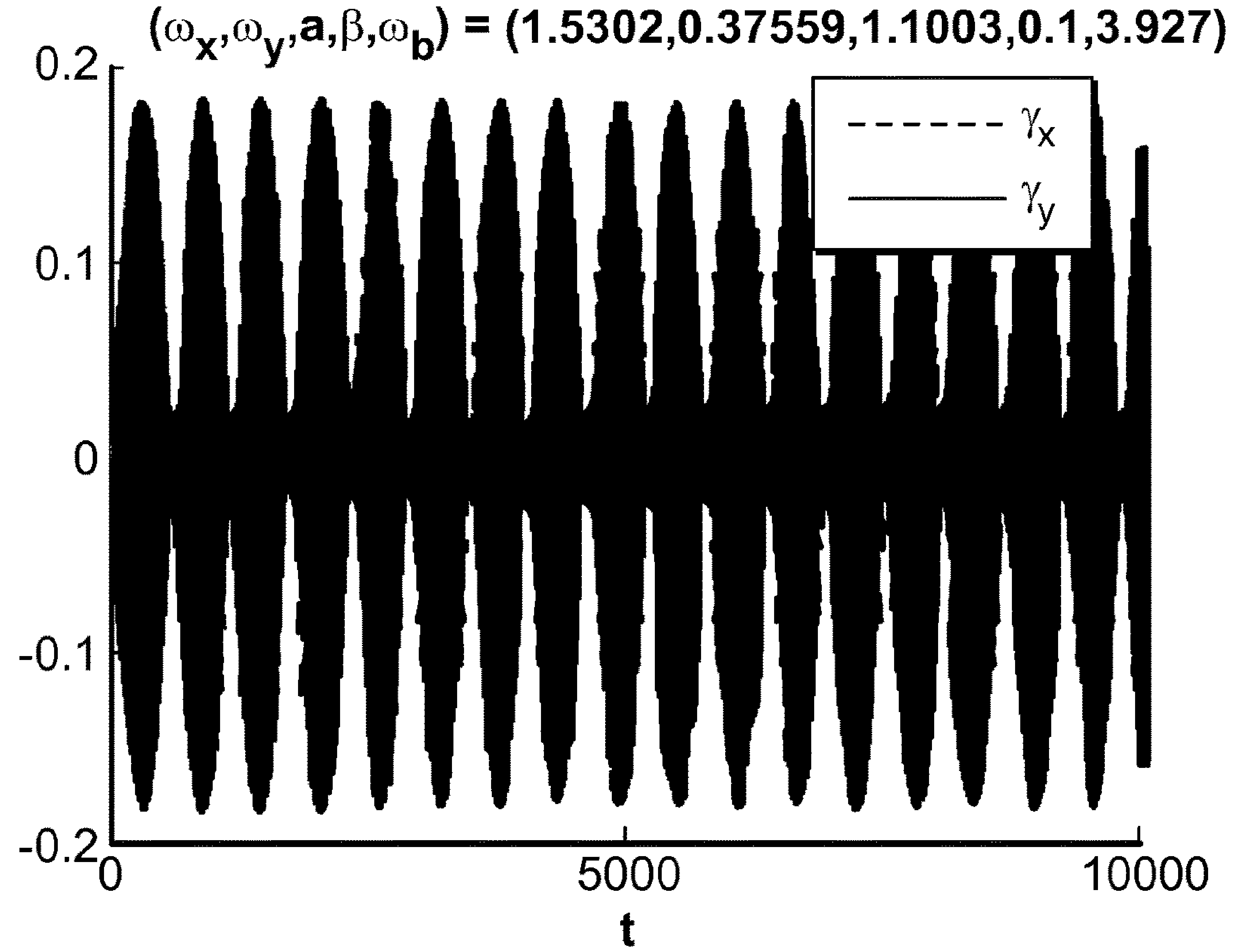


FIG. 14F

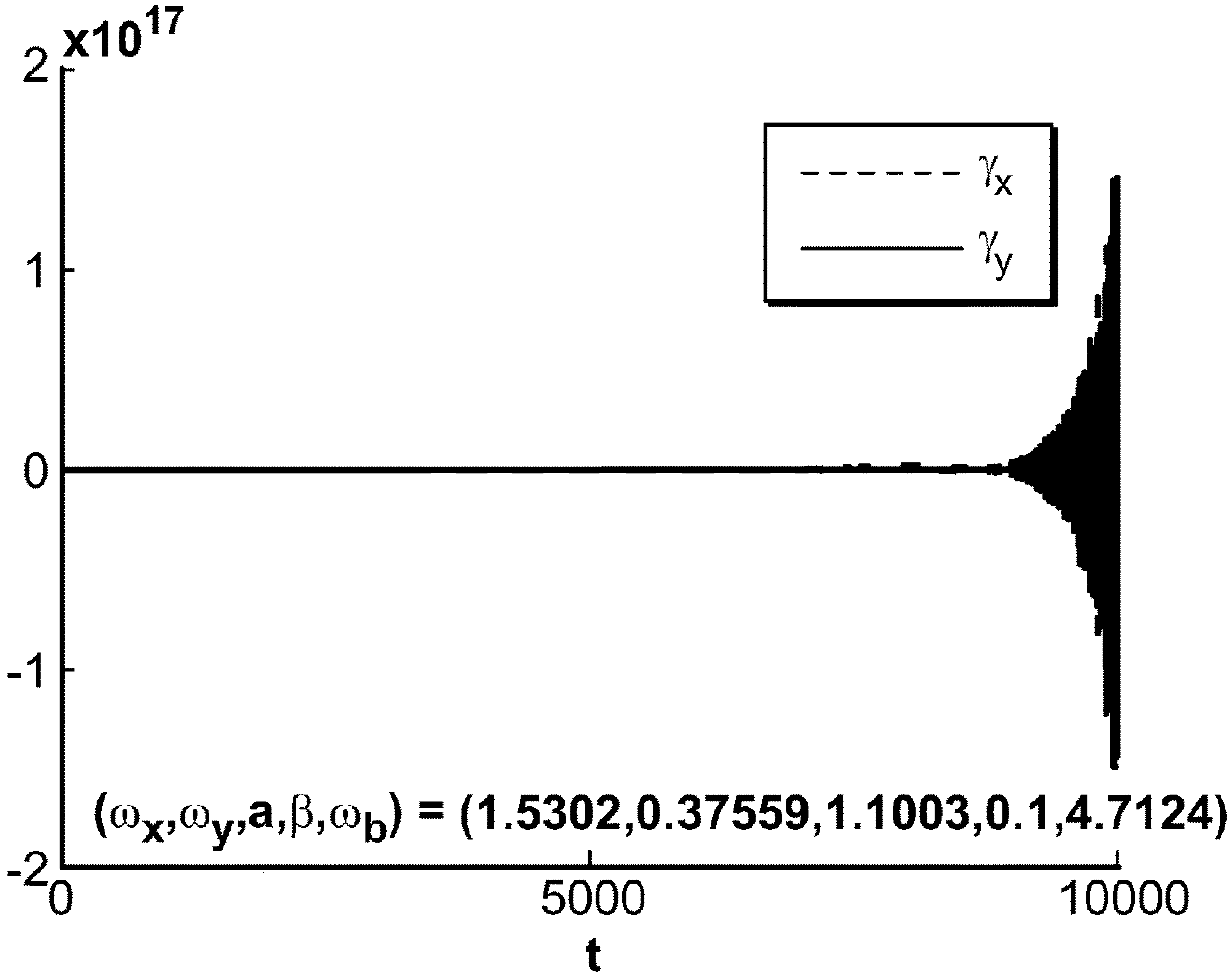


FIG. 14G

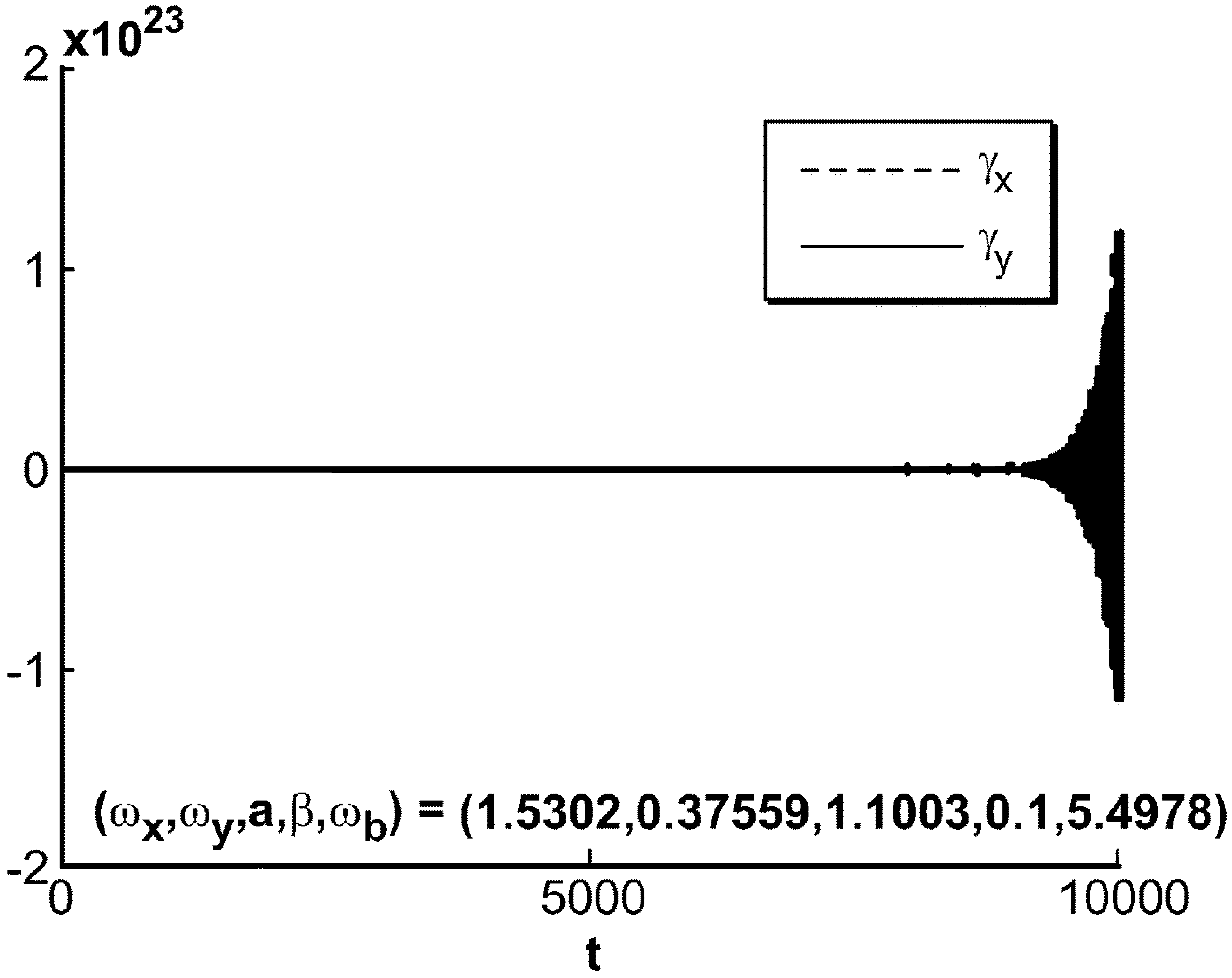


FIG. 14H

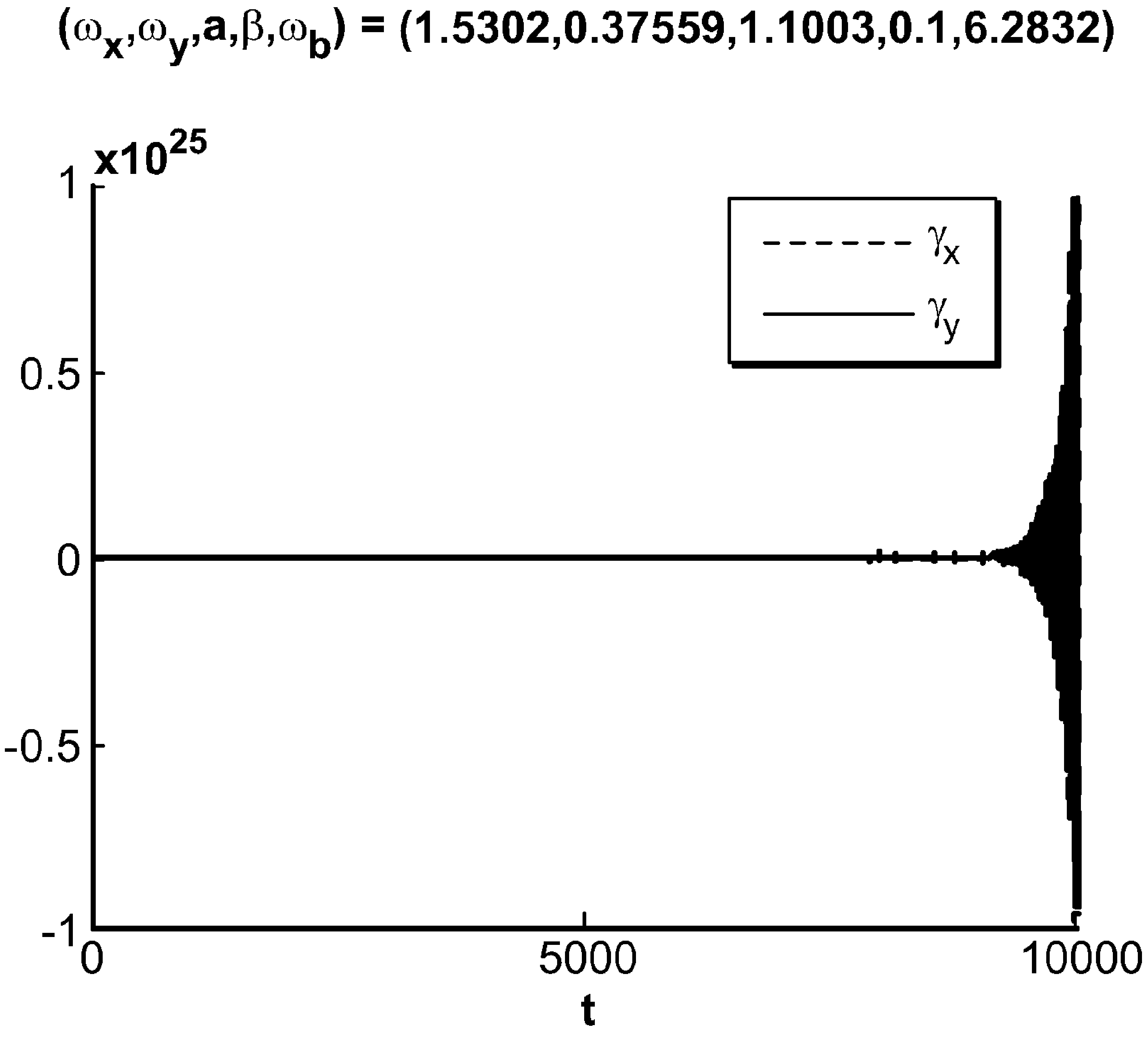

$(\omega_x,\omega_y,a,\beta,\omega_b)$ = (1.5302,0.37559,1.1003,0.1,6.2832)
$x10^{25}$
1
0.5
0
-0.5
-1
0
5000
10000
t
γ_x
γ_y

FIG. 14I

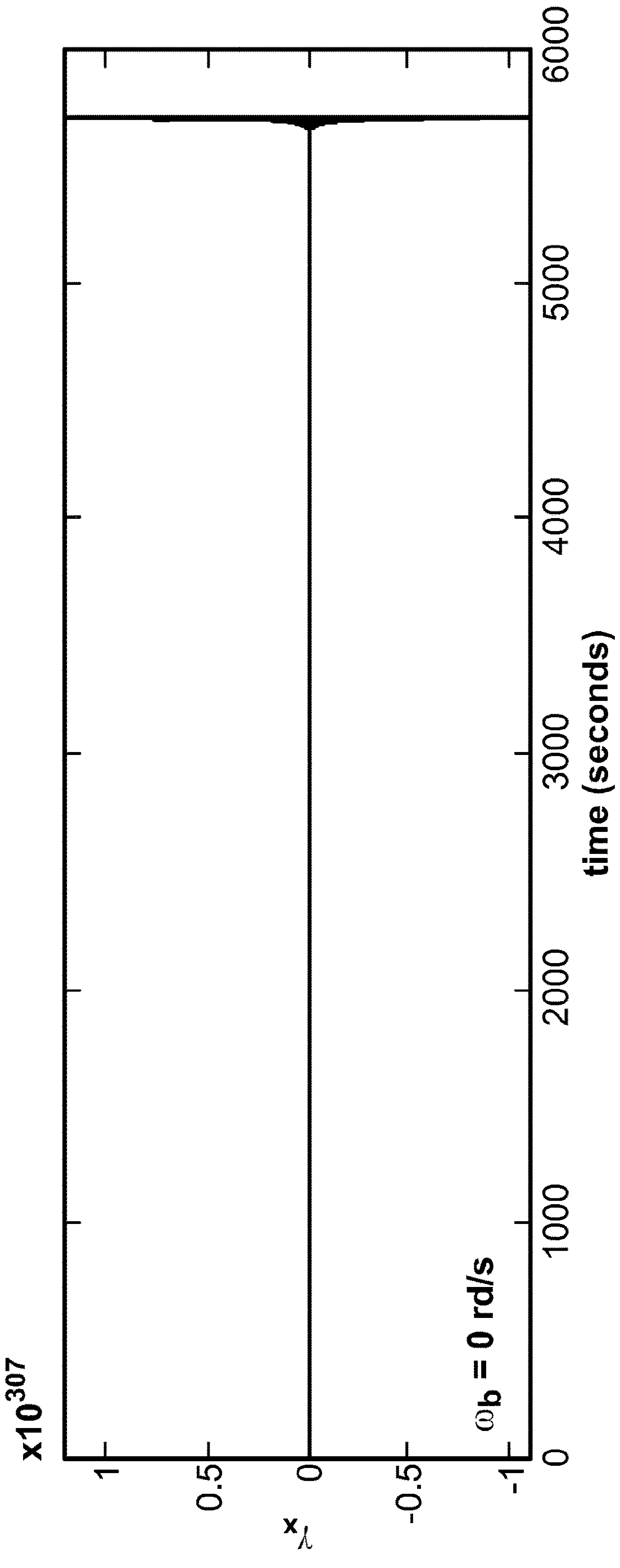

x10^307
1
0.5
0
-0.5
-1
x_λ
ω_b = 0 rd/s
0
1000
2000
3000
4000
5000
6000
time (seconds)

FIG. 15A

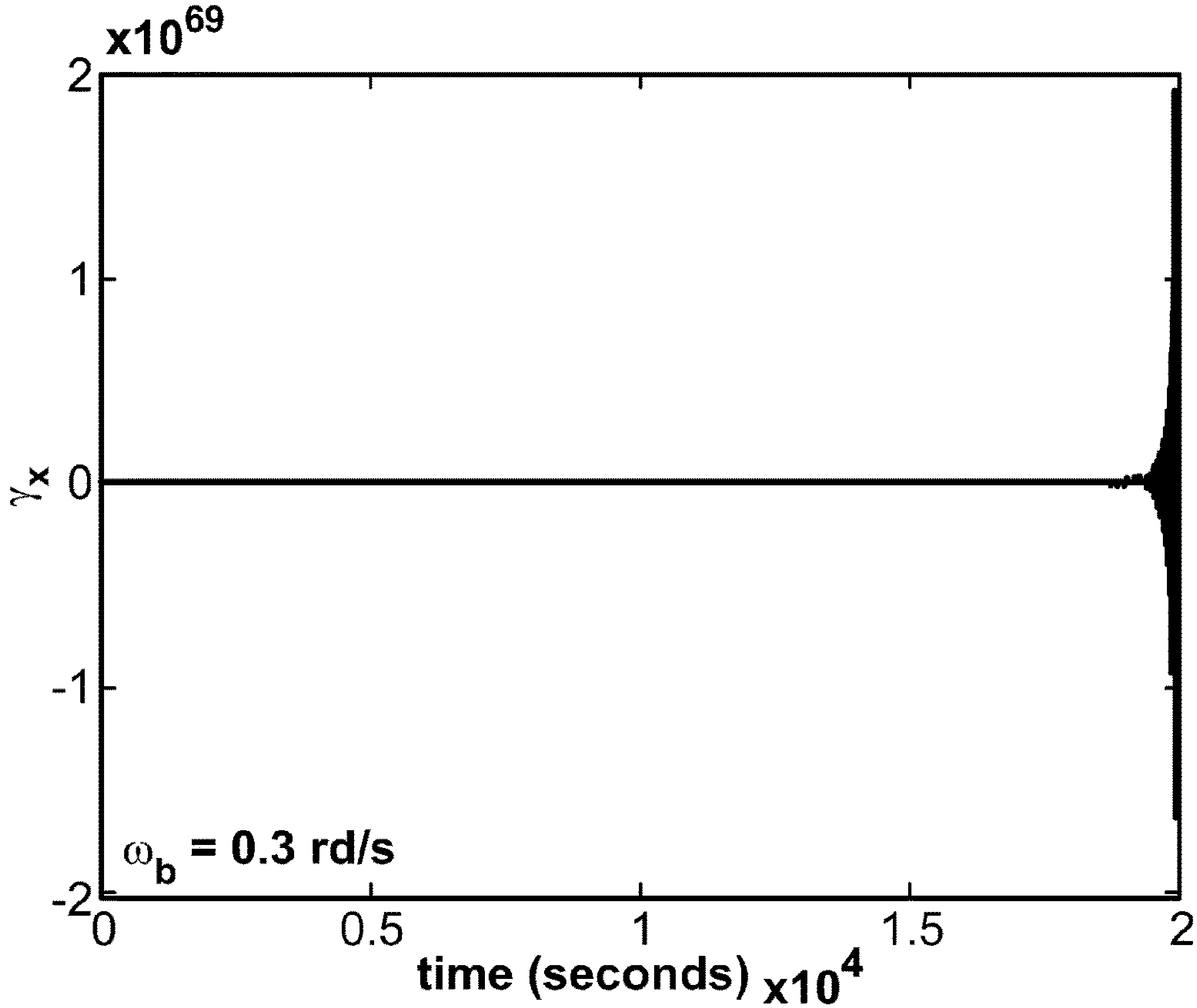


FIG. 15B

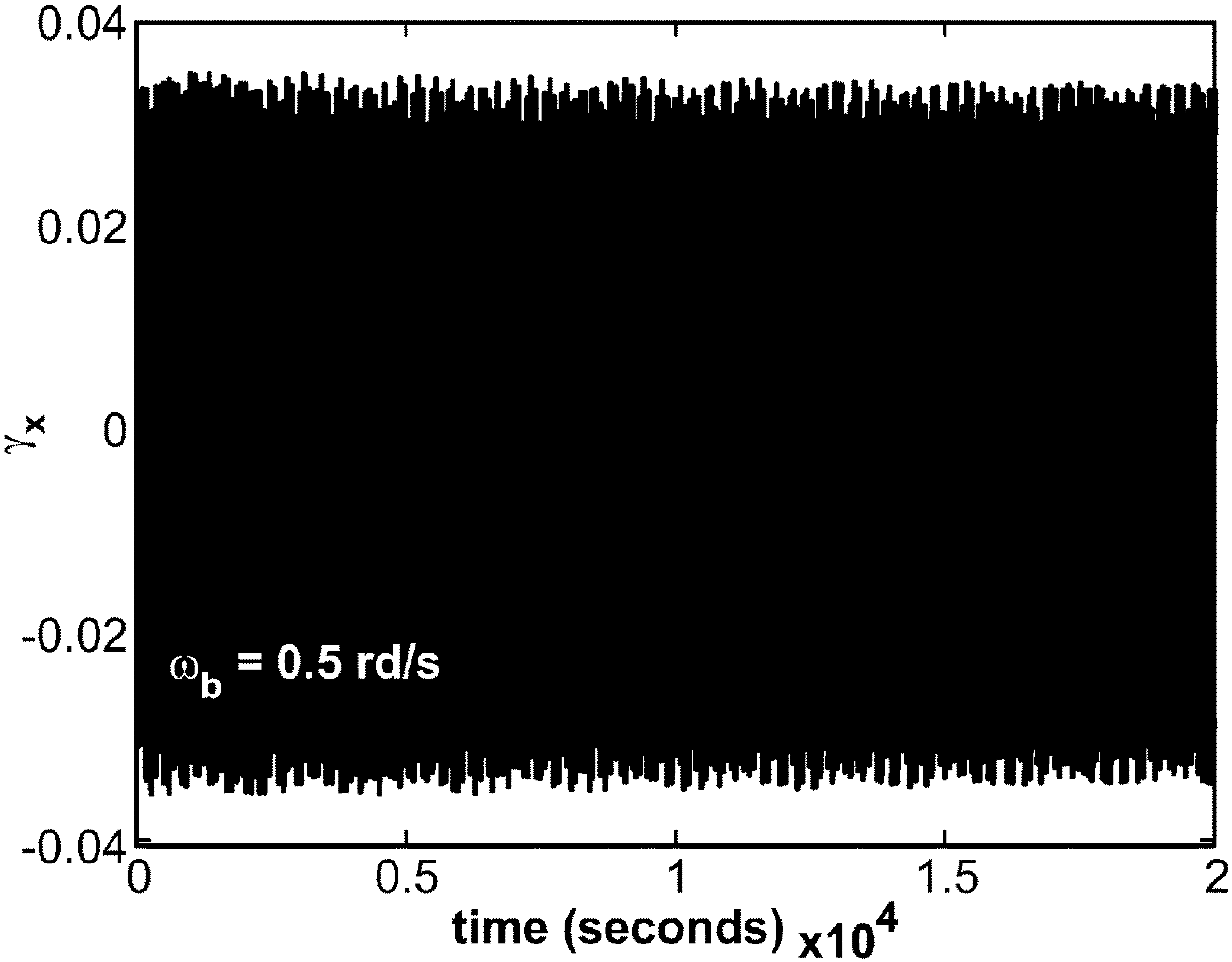


FIG. 15C

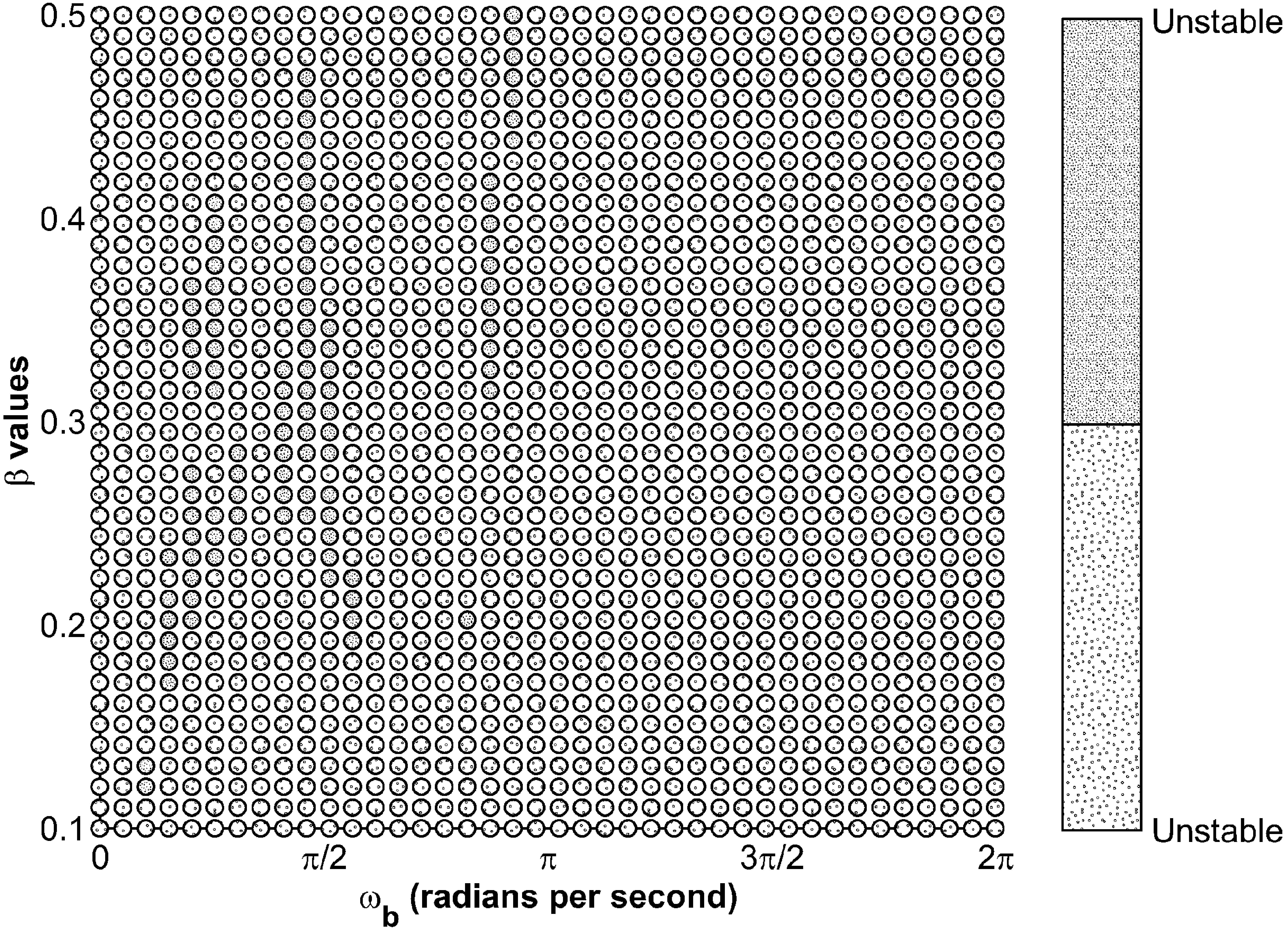

0.5
0.4
0.3
0.2
0.1
β values
0
π/2
π
3π/2
2π
ω_b (radians per second)
Unstable
Unstable

FIG. 16

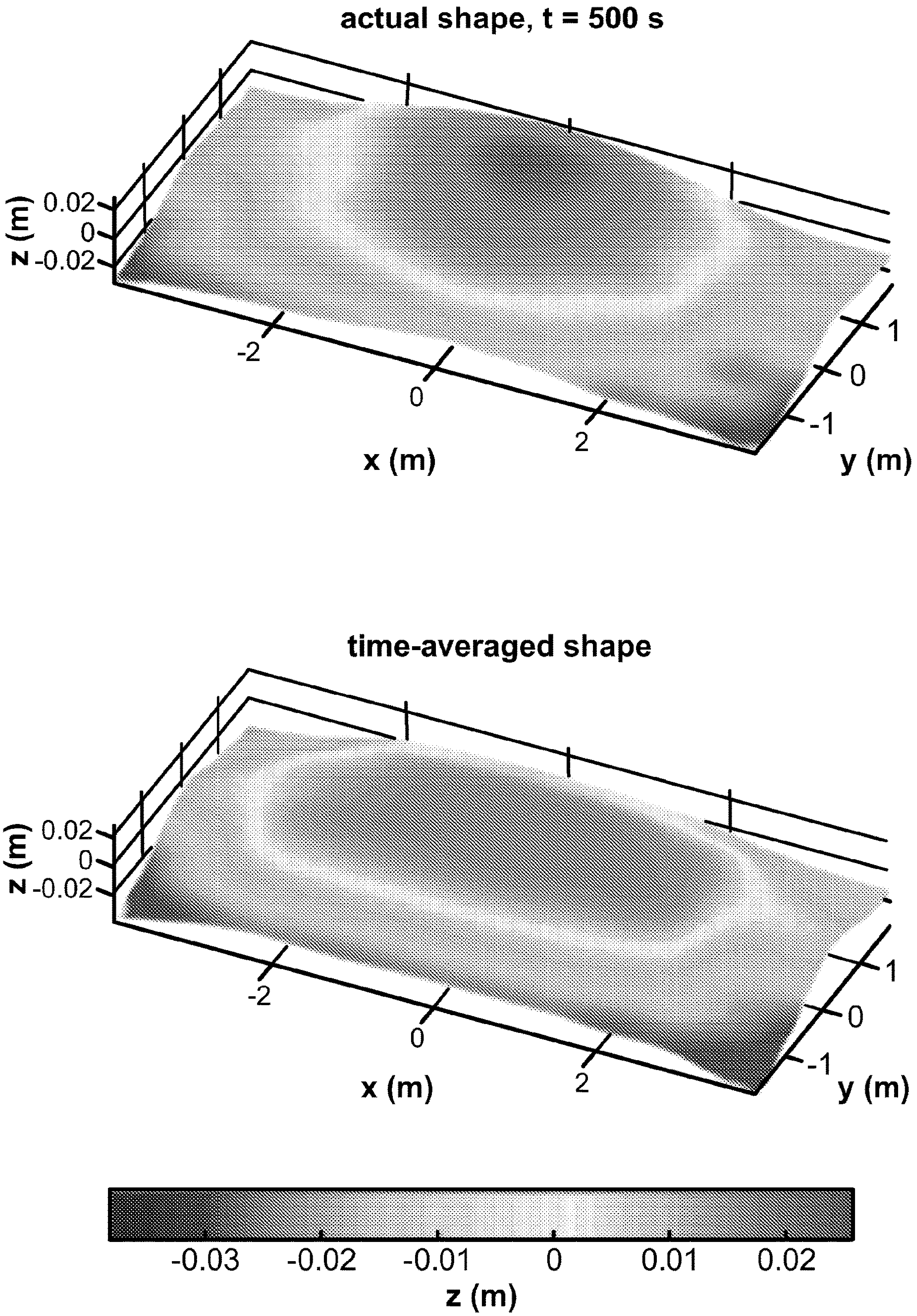

actual shape, t = 500 s
z (m)
0.02
0
-0.02
-2
0
2
x (m)
1
0
-1
y (m)
time-averaged shape
z (m)
0.02
0
-0.02
-2
0
2
x (m)
1
0
-1
y (m)
-0.03
-0.02
-0.01
0
0.01
0.02
z (m)

FIG. 17

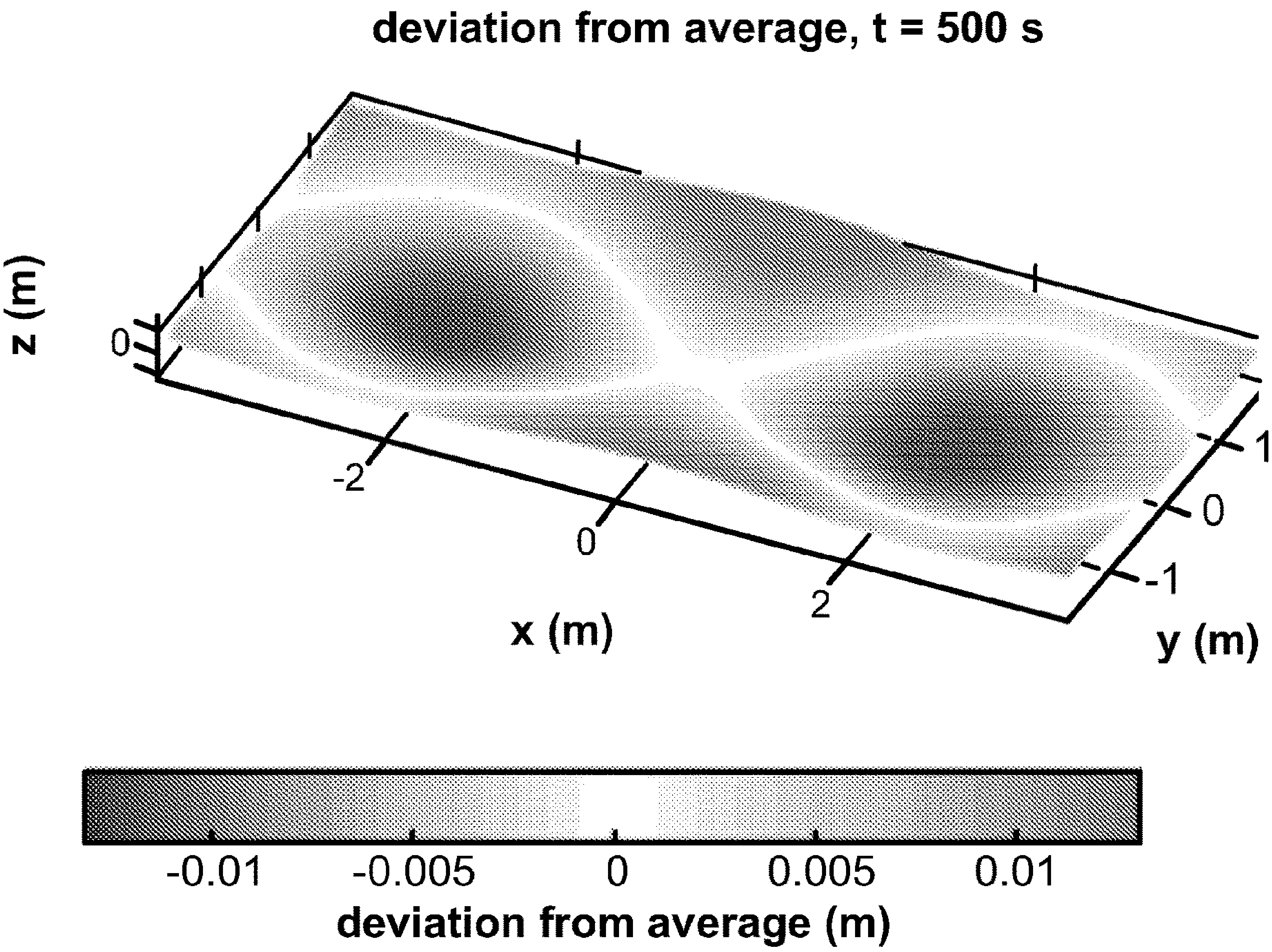

deviation from average, t = 500 s
z (m)
0
-2
0
2
x (m)
1
0
-1
y (m)
-0.01
-0.005
0
0.005
0.01
deviation from average (m)

FIG. 17
(Cont'd)

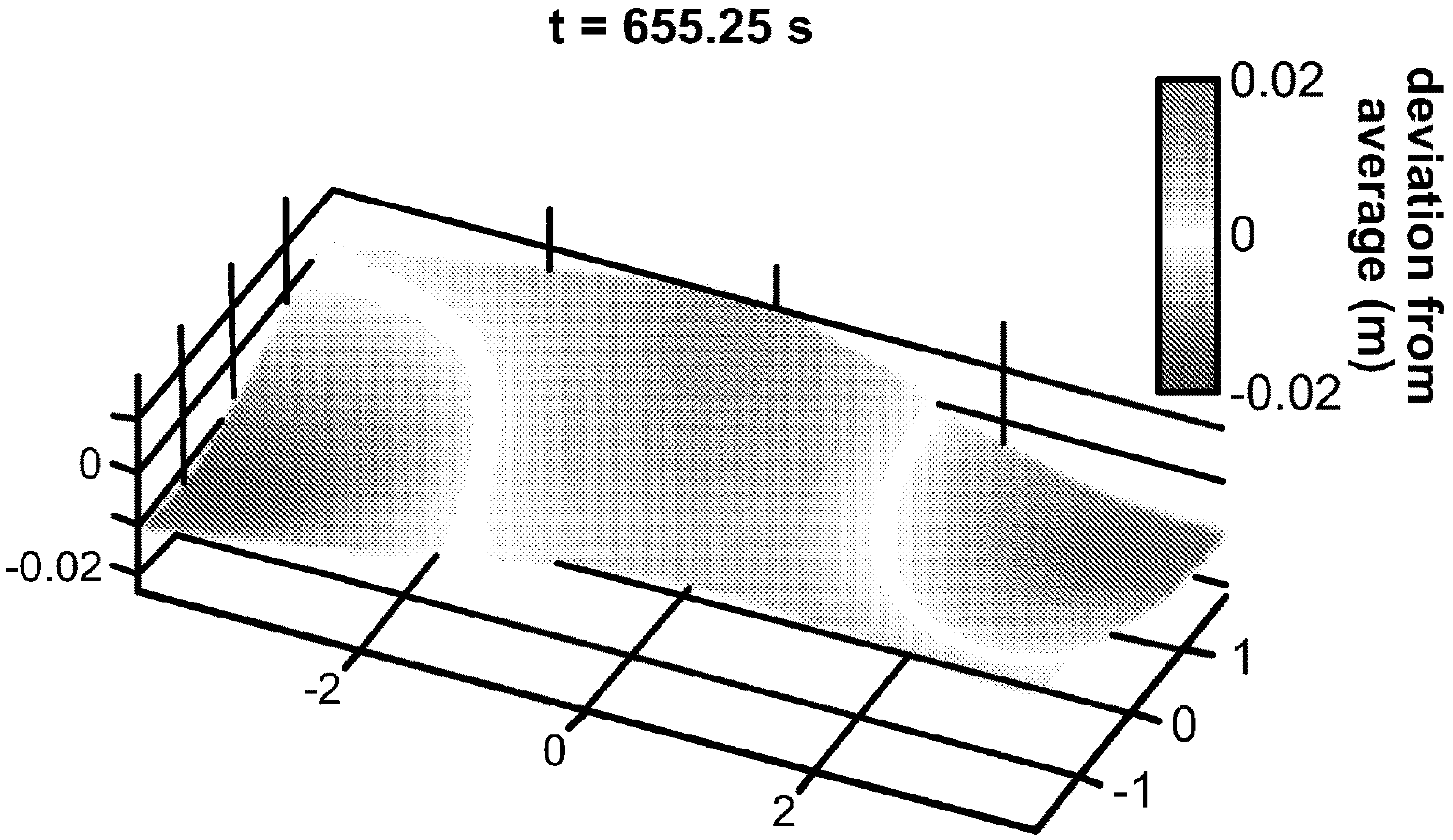


FIG. 18A

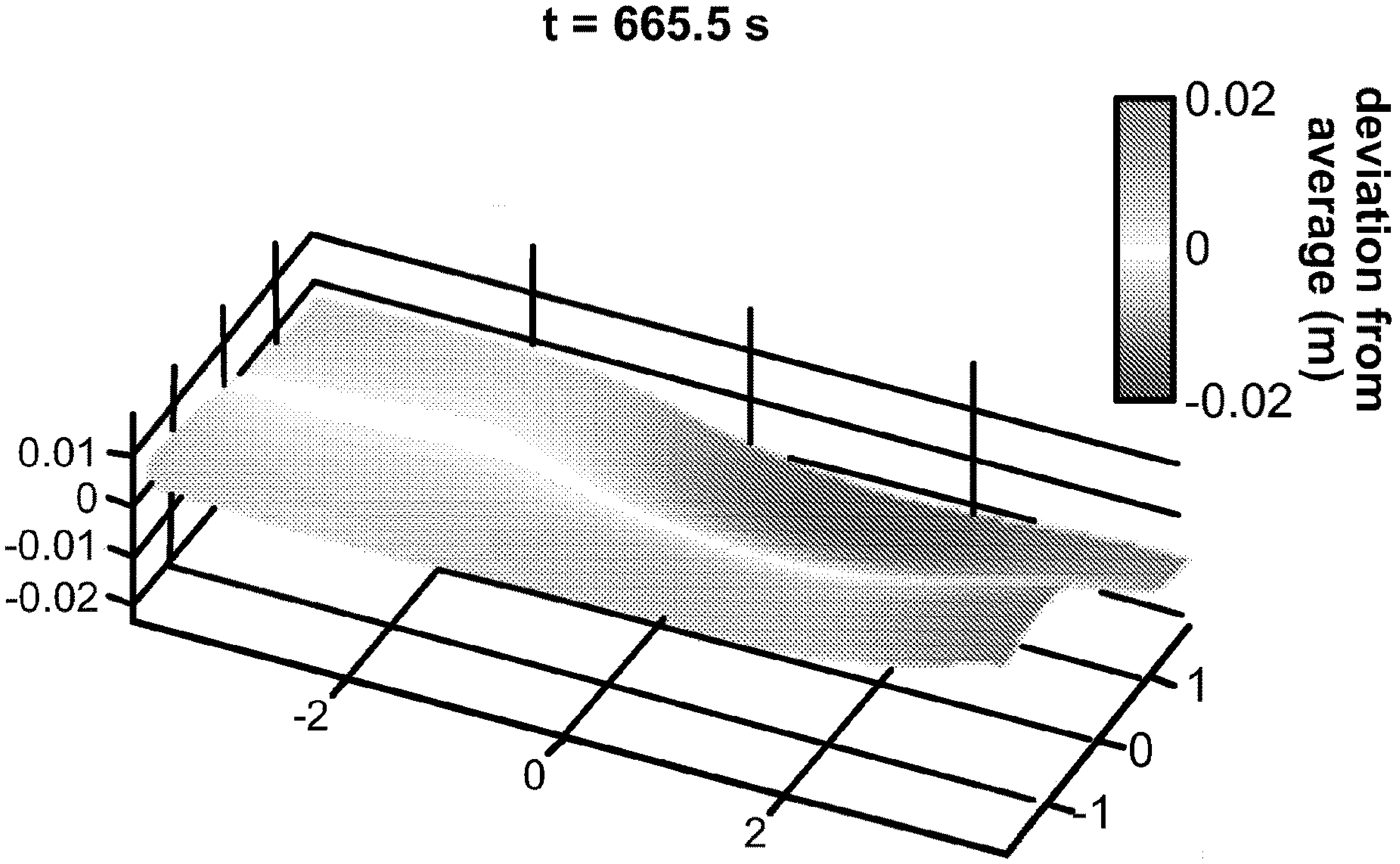


FIG. 18B

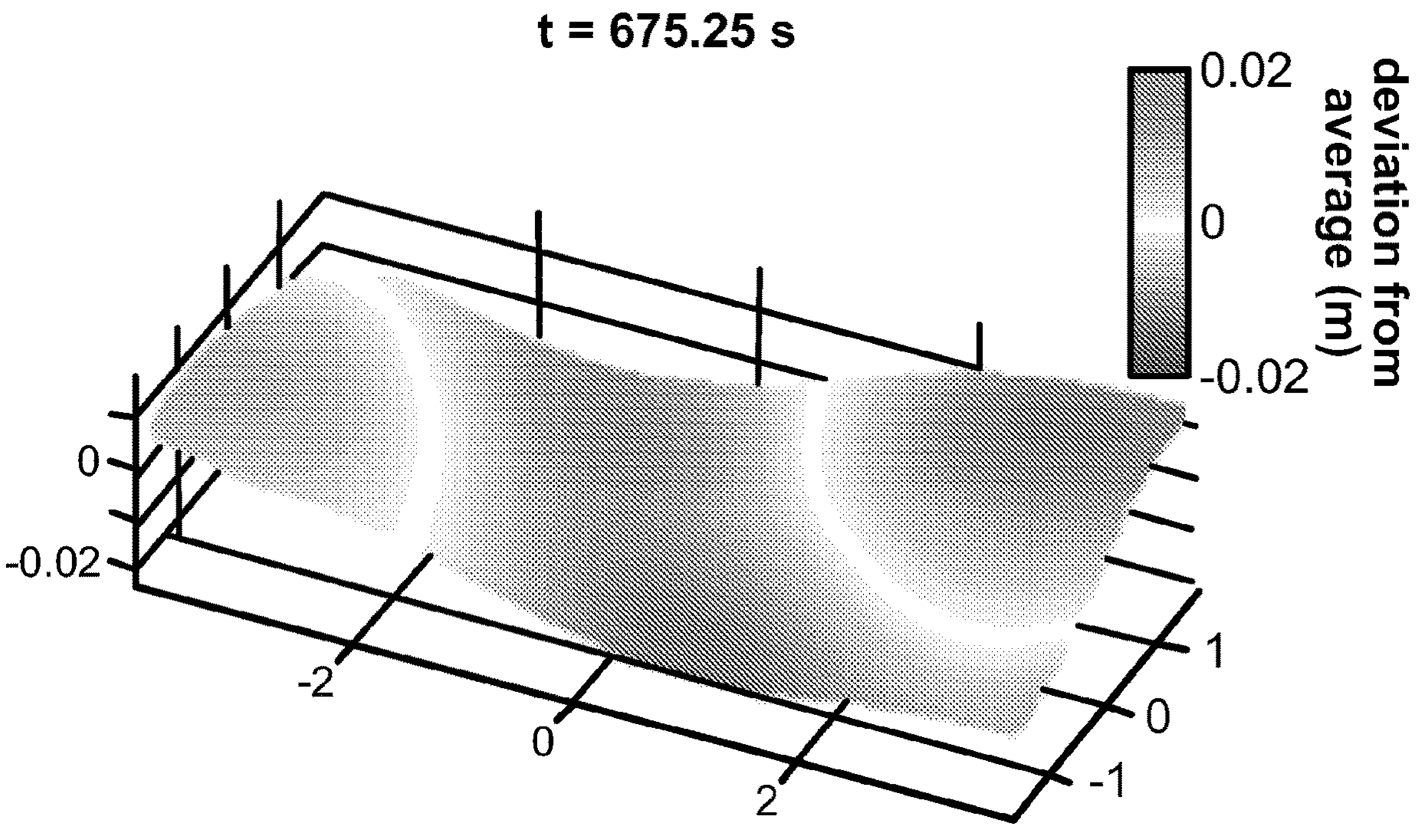


FIG. 18C

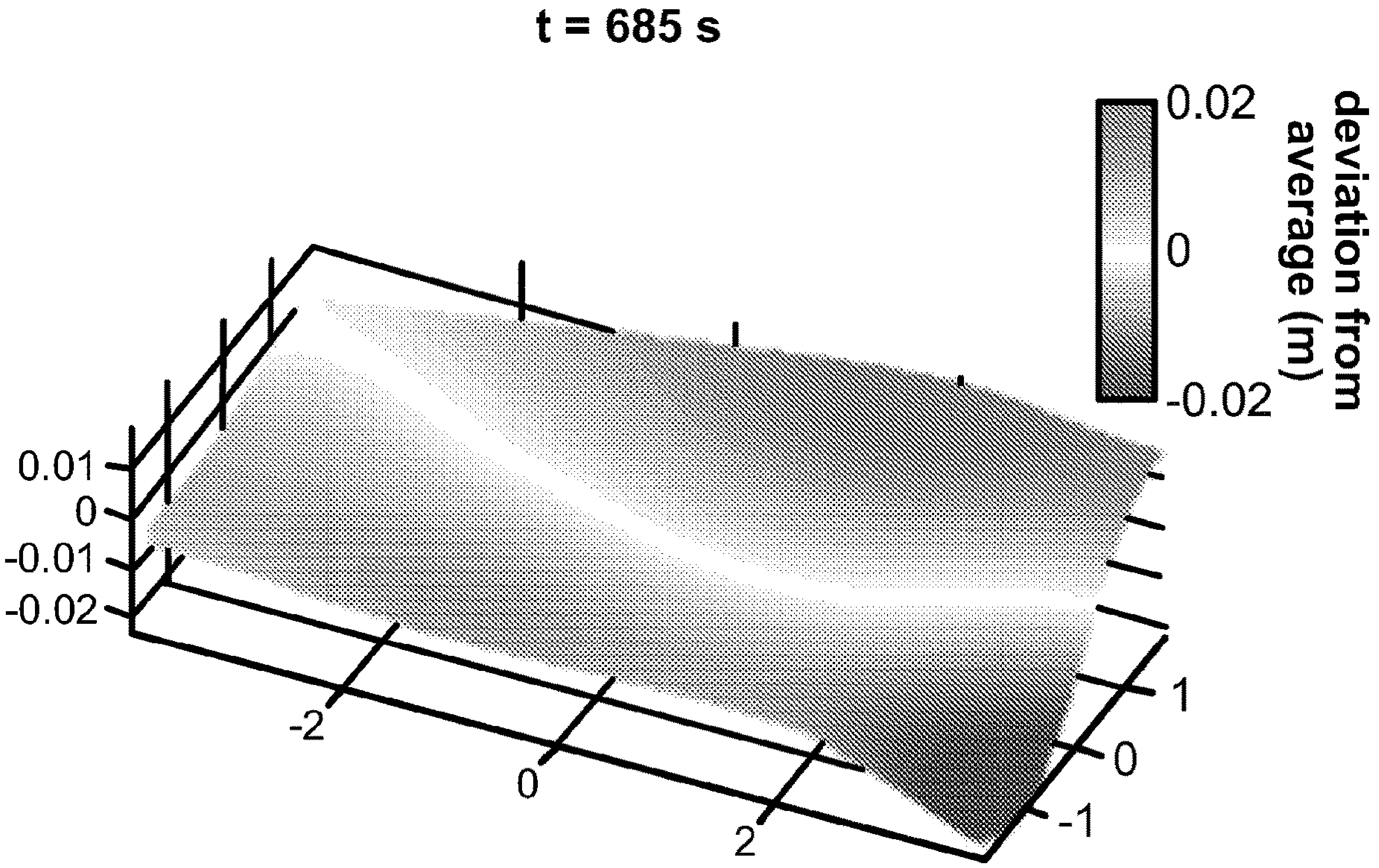


FIG. 18D

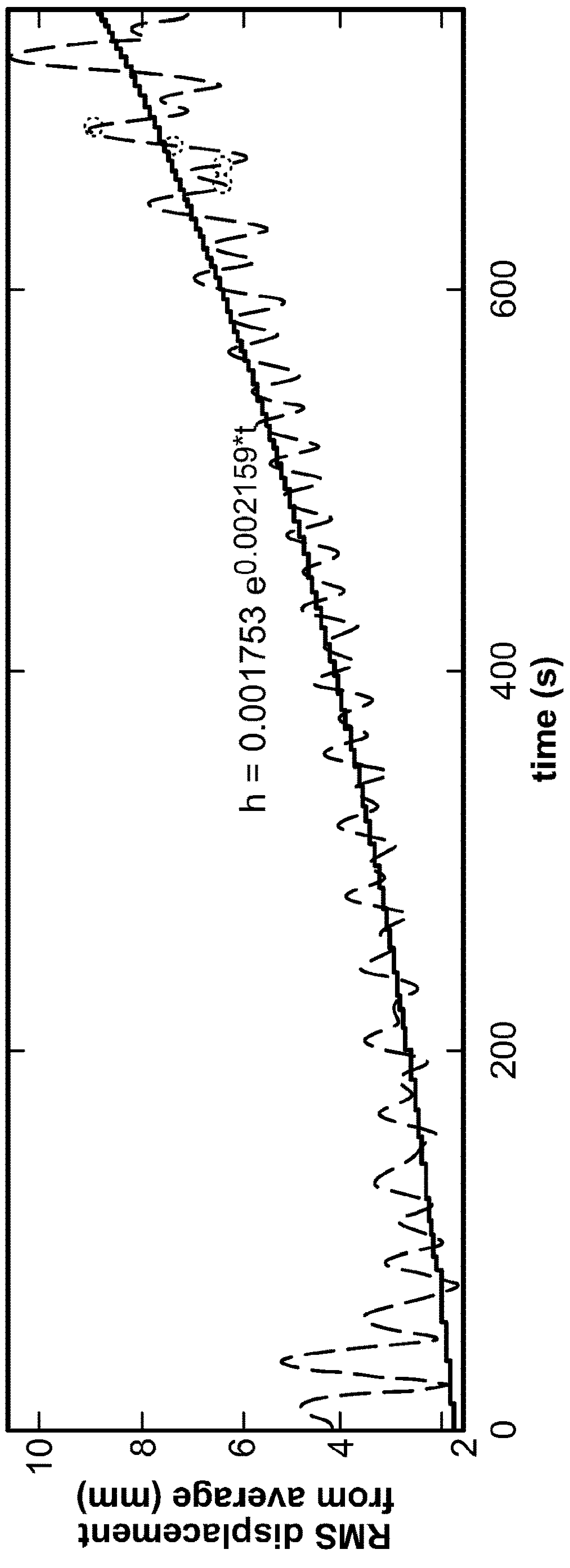

RMS displacement from average (mm)
2
4
6
8
10
0
200
400
600
time (s)
h = 0.001753 e^0.002159*t

FIG. 18E

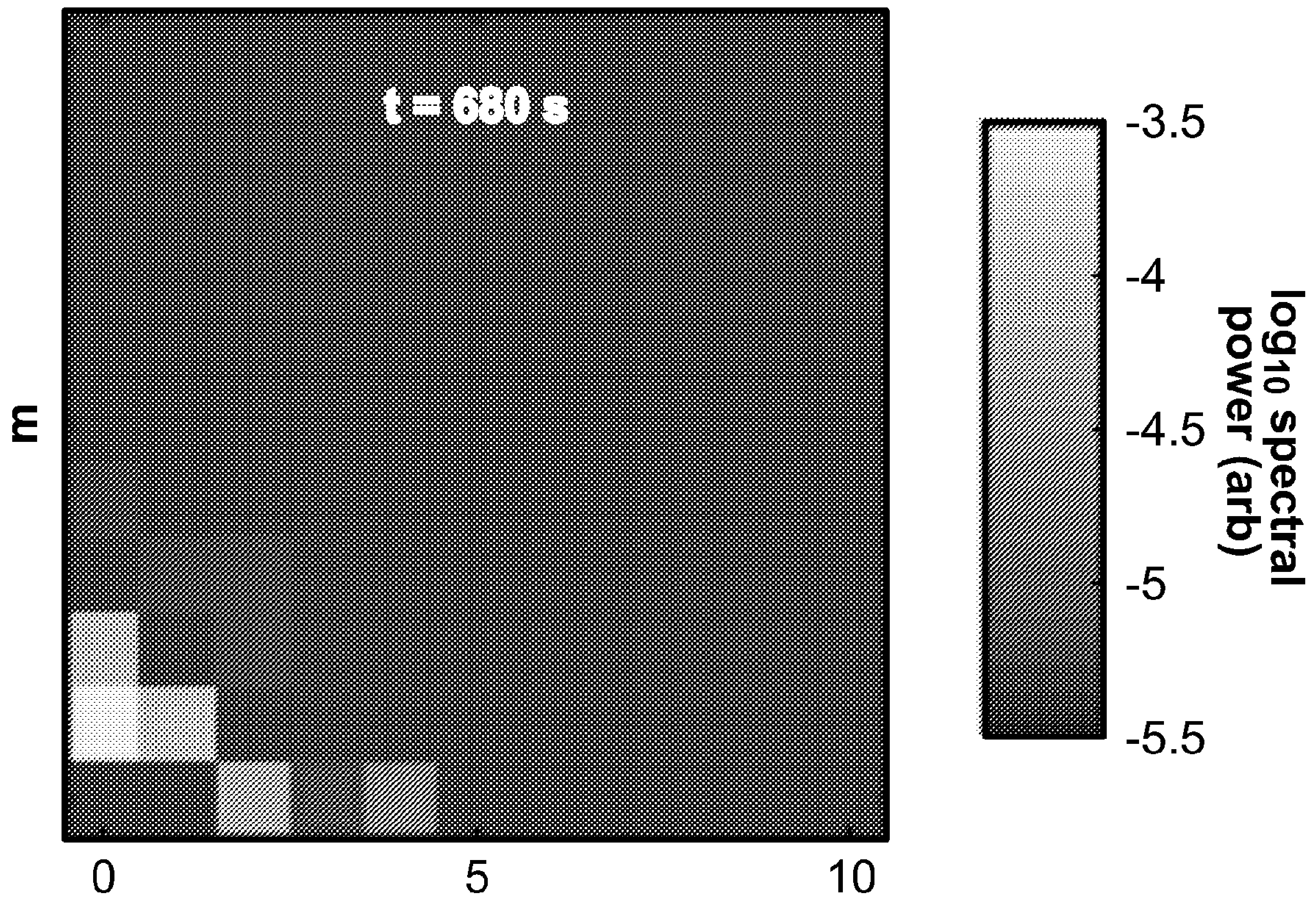


FIG. 18F

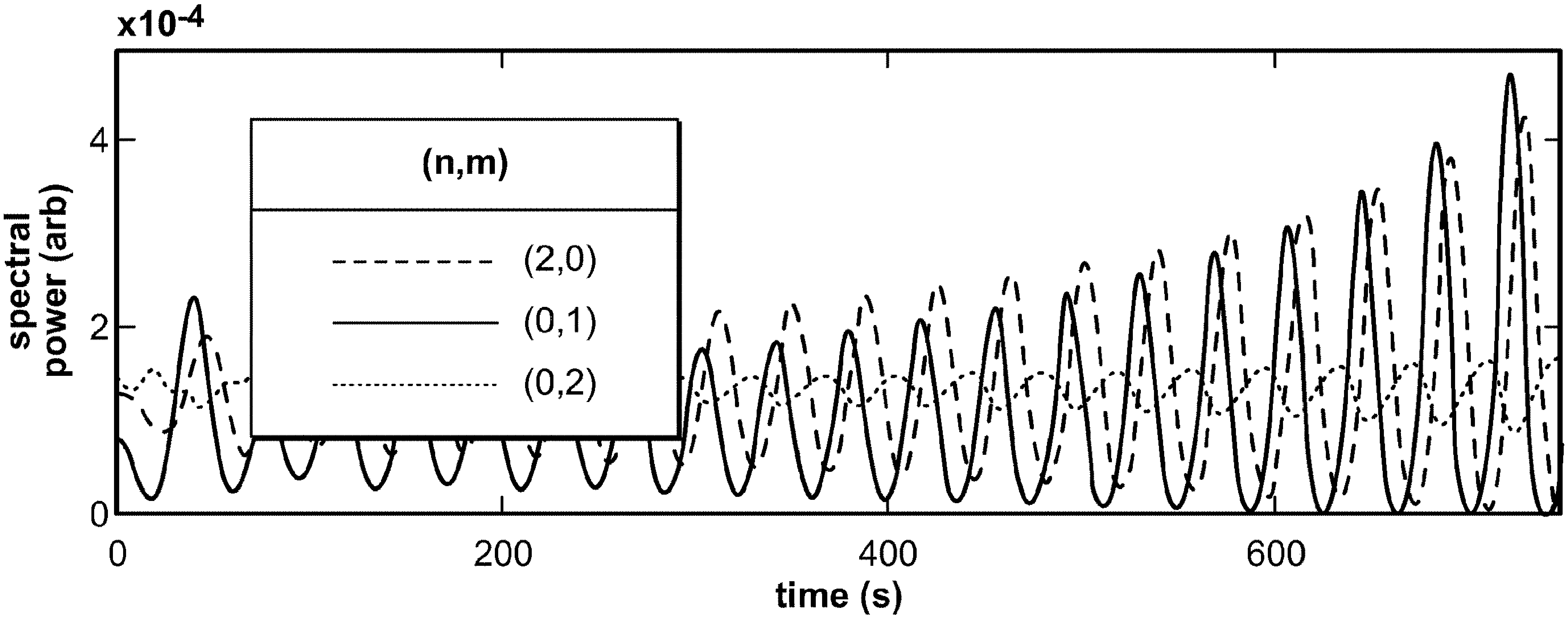


FIG. 18G

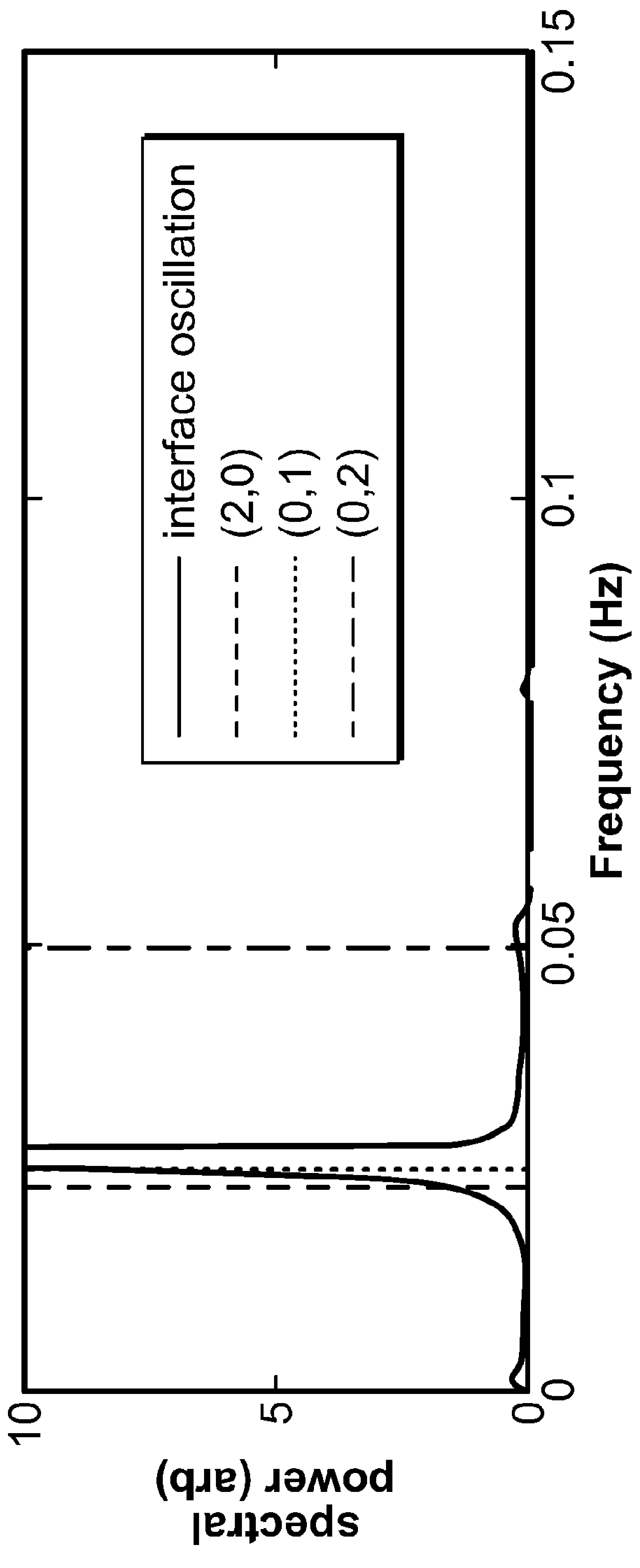

spectral power (arb)
10
5
0
0
0.05
0.1
0.15
Frequency (Hz)
interface oscillation
(2,0)
(0,1)
(0,2)

FIG. 18H

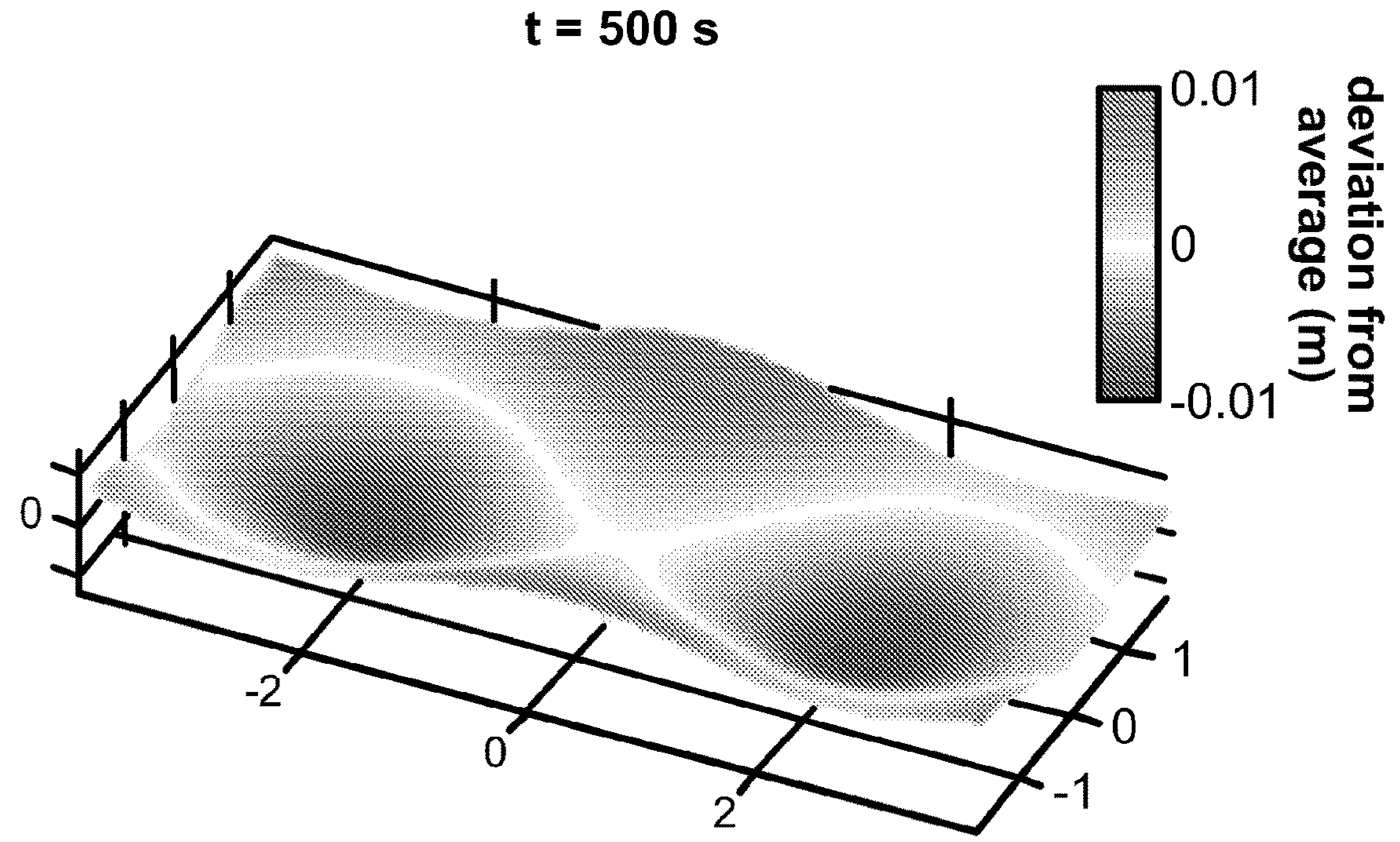


FIG. 19A

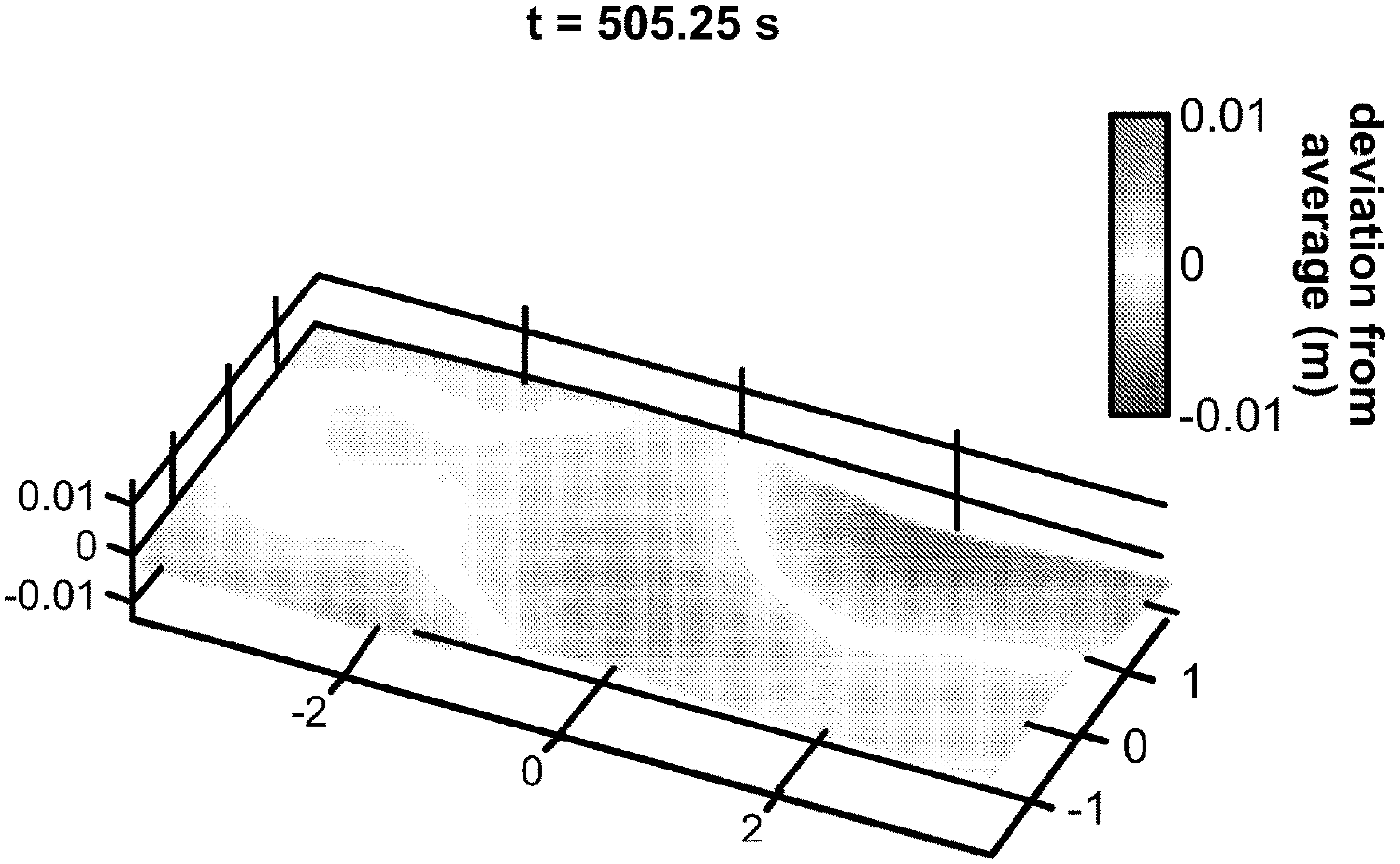


FIG. 19B

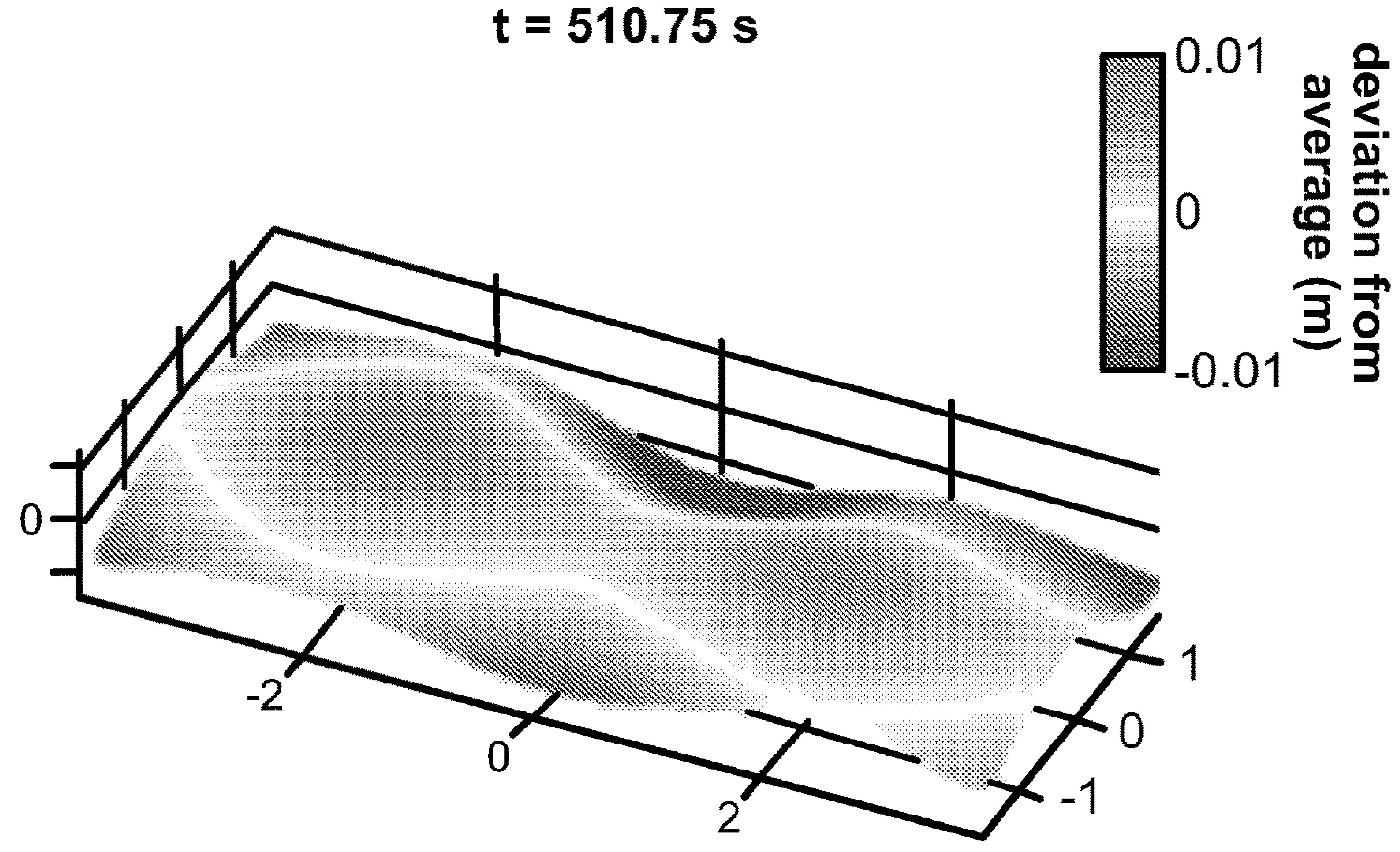


FIG. 19C

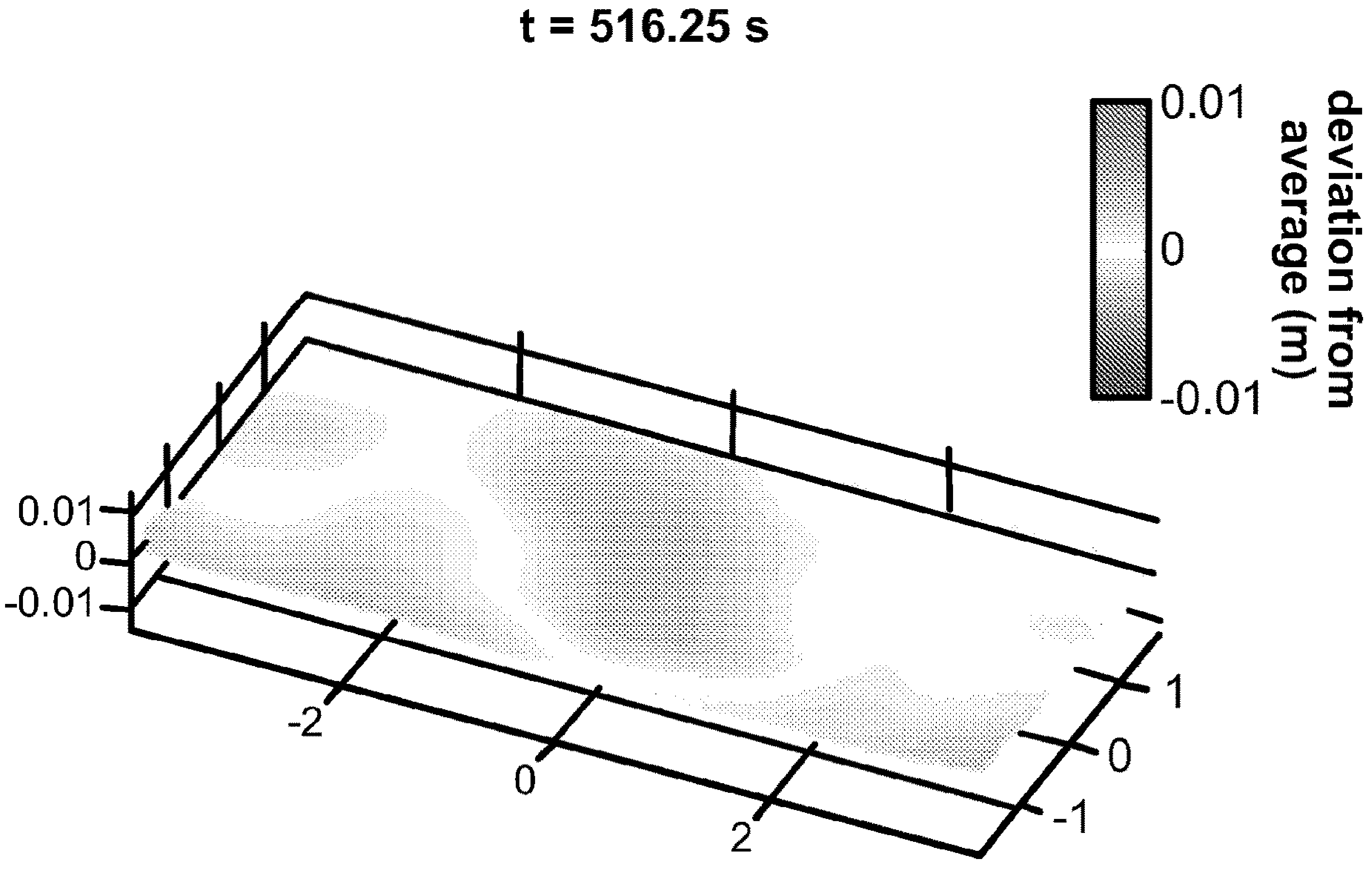


FIG. 19D

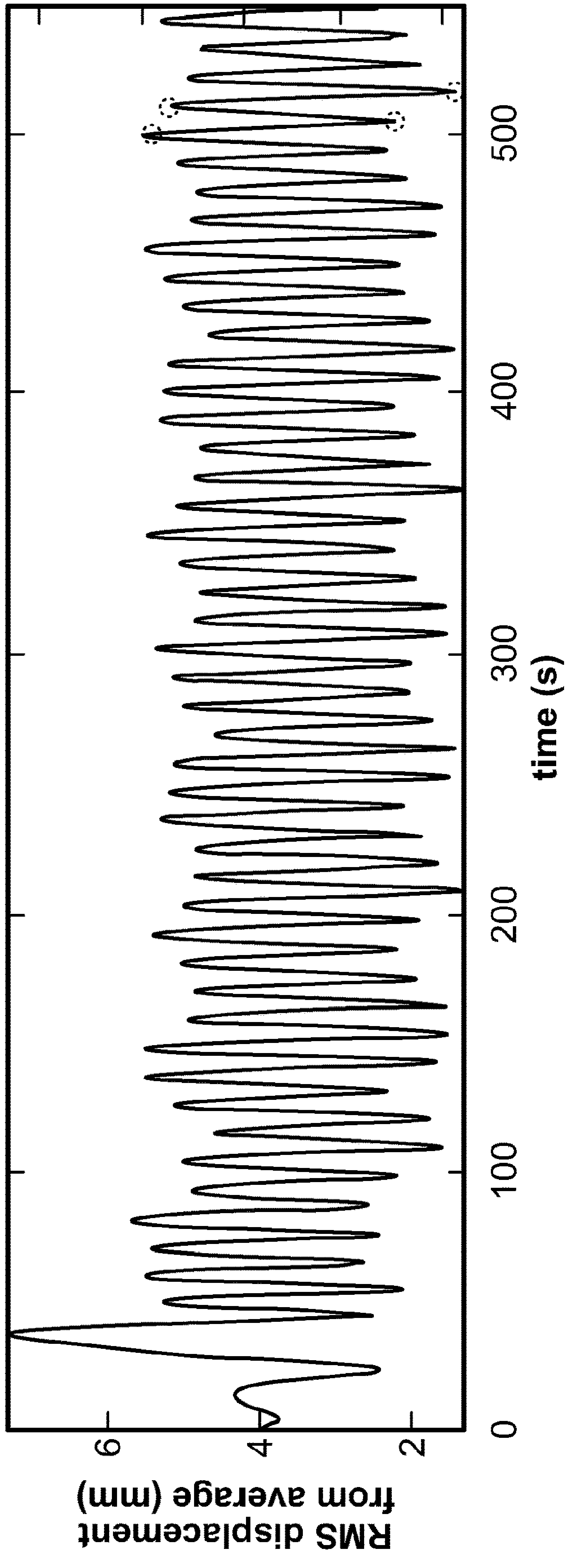

RMS displacement from average (mm)
6
4
2
0
100
200
300
400
500
time (s)

FIG. 19E

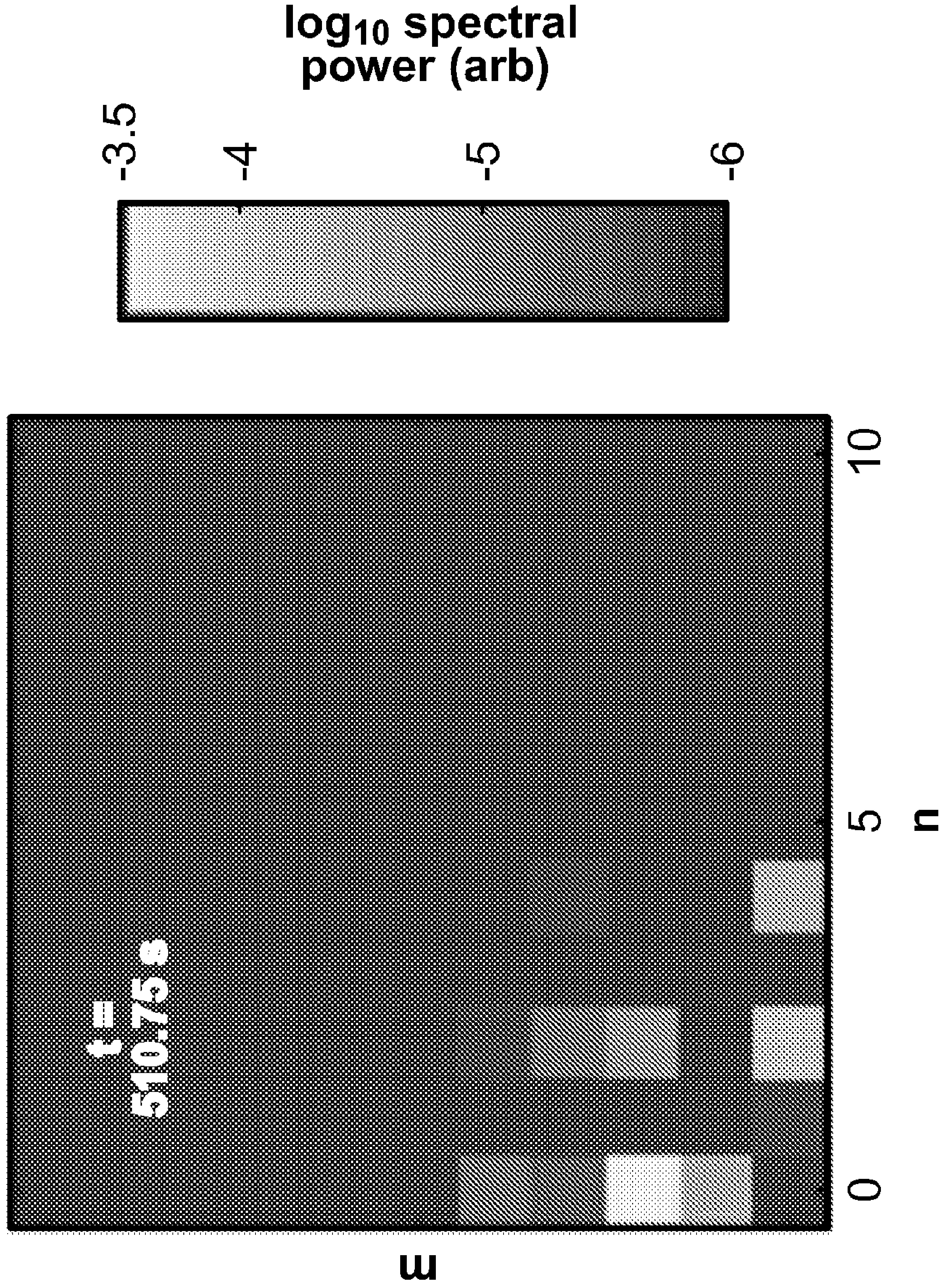


FIG. 19F

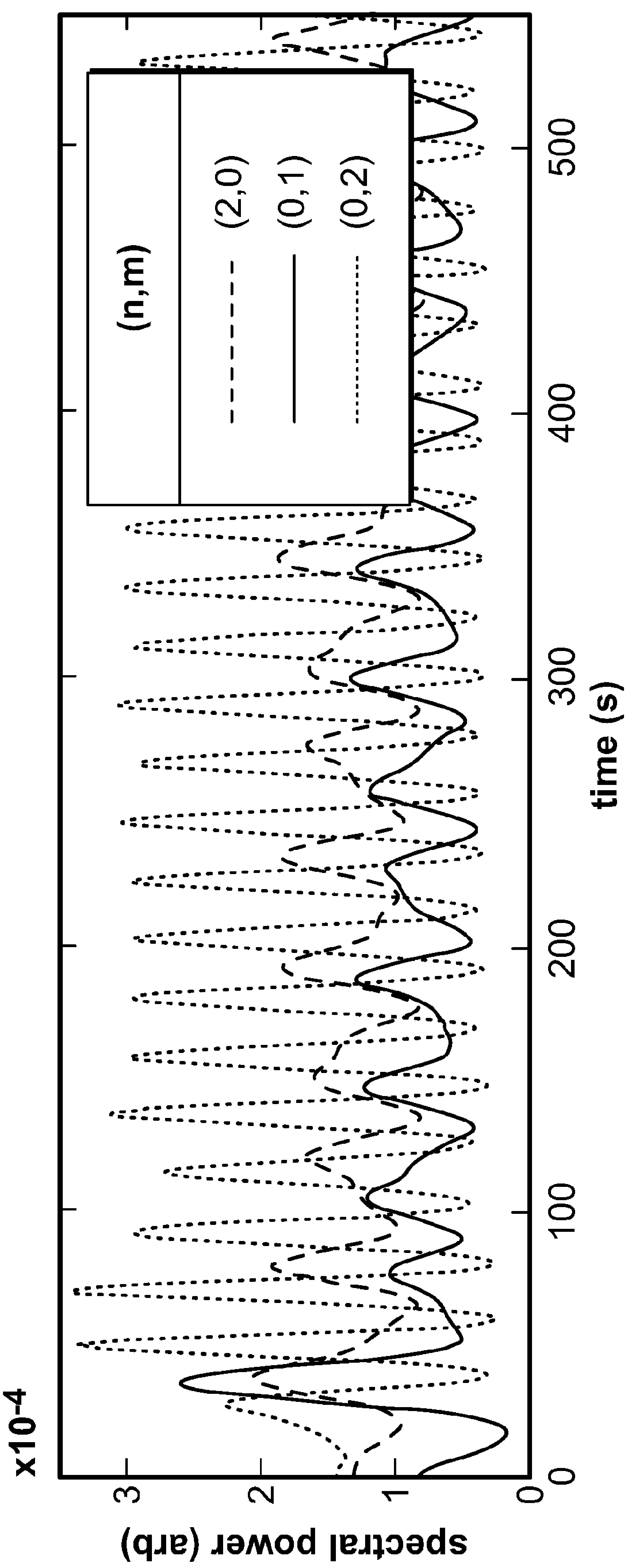

x10-4
spectral power (arb)
0
1
2
3
time (s)
0
100
200
300
400
500
(n,m)
(2,0)
(0,1)
(0,2)

FIG. 19G

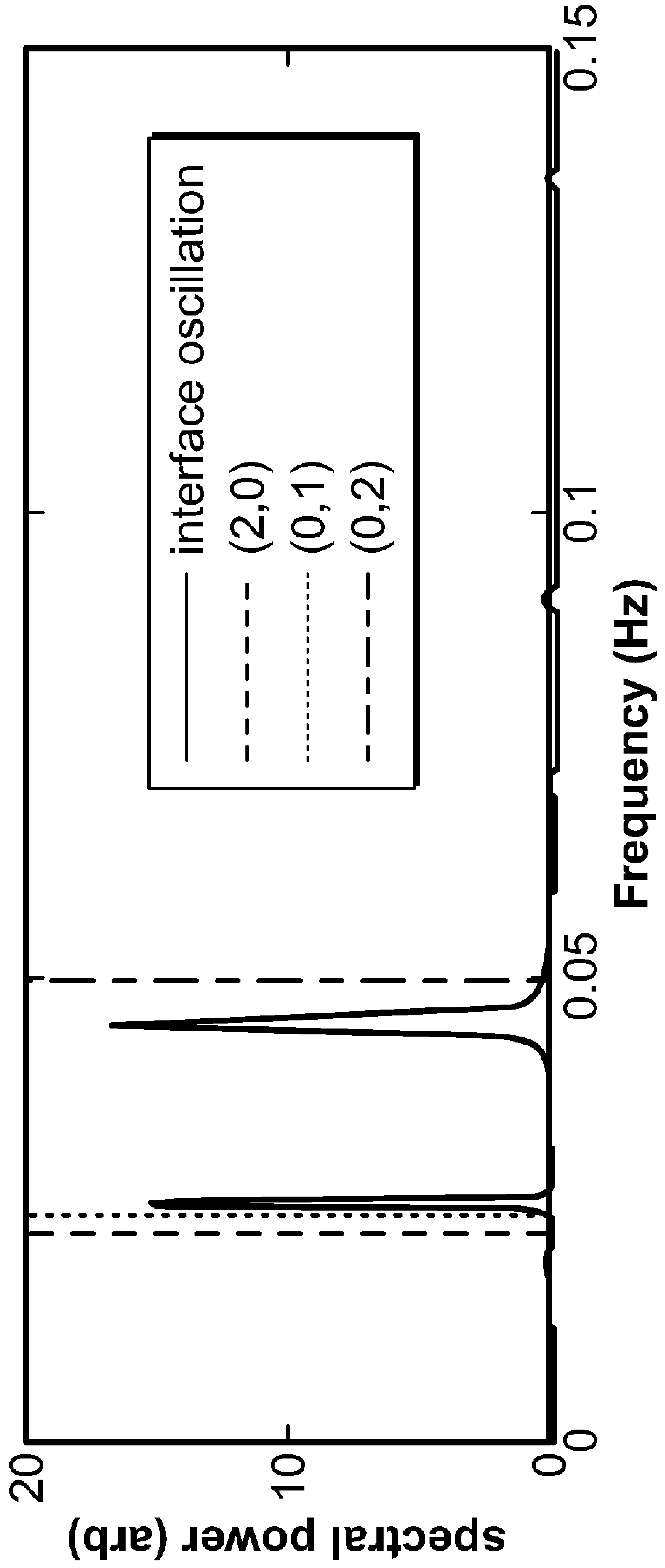

spectral power (arb)
20
10
0
0
0.05
0.1
0.15
Frequency (Hz)
interface oscillation
(2,0)
(0,1)
(0,2)

FIG. 19H

SYSTEMS AND METHODS FOR ENERGY EFFICIENT ELECTROLYSIS CELLS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/972,286, filed Feb. 10, 2020, the content of which is incorporated herein by reference in its entirety.

STATEMENT ACKNOWLEDGING GOVERNMENT SUPPORT

[0002] This invention was made with government support under Grant No. CBET-1552182 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

[0003] Currently, aluminum is produced by running large, steady (DC) electrical current through pools of molten salts atop liquid aluminum, a process that consumes about 3% of electricity worldwide (~10^{11} kWh/year) (P. A. DAVIDSON and R. I. LINDSAY. Stability of interfacial waves in aluminum reduction cells. *Journal of Fluid Mechanics,* 362:273-295, 1998). About 40% of that energy is wasted as heat in the salt and could be saved if the salt layer were thinner. Unfortunately, thinning the salt allows a resonant instability in which surface waves grow uncontrollably until the smelter is shut down.

[0004] Thus, there is a need for systems and methods for producing aluminum that allows reducing the thickness of the salt layer, and thus, increasing the efficiency of the energy consumption without a compromise in an aluminum smelter stability. These needs and other needs are at least partially satisfied by the present disclosure.

SUMMARY

[0005] The present invention is directed to a method comprising applying an alternating current (AC) comprising an oscillatory current waveform to an electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis.

[0006] In still further aspects, also disclosed herein is a method comprising: a) providing a first data to a computational processor, wherein the first data comprises at least one of one or more of geometric parameters of an electrolytic cell, a cathode-to-anode-distance of the electrolytic cell, a value of a direct current; an amplitude of a direct current, a thickness of a metal layer, material properties of a metal, material properties of an electrolyte, material properties of a cathode, material properties of an anode, or any combination thereof; b) analyzing the first data by the computational processor to provide a second data comprising parameters of an alternating current (AC) wherein the parameters comprise one or more of a first amplitude, a first frequency, and/or a first phase of an oscillatory current form of the AC; and c) applying the AC having one or more parameters present in the second data to the electrolytic cell to stabilize the electrolytic cell. In yet further aspects, the method is further comprises d) collecting a third data from the electrolytic cell and transferring the third data to the computational processor to analyze the performance of the electrolytic cell; e) analyzing the third data by the computational processor to provide a fourth data comprising parameters of the alternating current (AC) wherein the parameters comprise one or more of a second amplitude, a second frequency, and/or a second phase of an oscillatory current form of the AC; and f) applying the AC having one or more parameters present in the fourth data to the electrolytic cell.

[0007] In yet further aspects disclose is also a method for increasing energy efficiency in an electrolytic cell comprising: applying an alternating current (AC) comprising an oscillatory current waveform to the electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis; and wherein the energy efficiency is increased by at least about 5% when compared to a substantially identical reference electrolytic cell in the absence of applying an AC.

[0008] In yet further aspects, disclosed is a system comprising: a) an electrolytic cell comprising: i) an anode; iii) a cathode; and iii) an electrolyte having a predetermined thickness; b) a direct current source that is in electrical communication with the electrolytic cell and is configured to provide a direct current (DC) having a predetermined amplitude and to initiate an electrolysis reaction in the electrolytic cell; c) a device comprising an alternating current source (AC); wherein the device is in electrical communication with the electrolytic cell and is configured to provide an alternating current (AC) to the electrolytic cell, wherein the AC comprises an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase; and wherein the device is in feedback loop communication with the electrolytic cell; and wherein the electrolytic cell exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell.

[0009] In still further aspects, the disclosed herein electrolytic cell is an aluminum electrolysis cell. In yet some aspects, the molten salt electrolyte comprises cryolite. In yet further aspects, the predetermined thickness of the molten electrolyte can be equal to or less than about 4.5 cm.

[0010] Additional aspects of the disclosure will be set forth, in part, in the detailed description, figures, and claims which follow, and in part will be derived from the detailed description, or can be learned by practice of the invention. It is understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention as disclosed.

BRIEF DESCRIPTION OF DRAWINGS

[0011] FIG. **1** a schematic of Hall-Heroult cell (H-H cell) (according to P. A. DAVIDSON et al., “Stability of interfacial waves in aluminium reduction cells.” *Journal of Fluid Mechanics,* 362:273-295, 1998).

[0012] FIG. **2** depicts an exemplary schematic diagram of an exemplary system in one aspect.

[0013] FIG. **3** depicts an exemplary schematic diagram of an exemplary system in one aspect.

[0014] FIG. **4** depicts a diagram of an exemplary mechanical model that is analogous to the sloshing instability in aluminium cells (according to P. A. DAVIDSON et al., "Stability of interfacial waves in aluminium reduction cells." *Journal of Fluid Mechanics,* 362:273-295, 1998).

[0015] FIGS. **5A**-**5C** depict exemplary models in one embodiment: FIG. **5A**—a model of the unperturbed state; FIG. **5B**—a model under small rotation about x-axis; and FIG. **5C**—a model under small rotation about the y-axis.

[0016] FIGS. **6A**-**6B** depict exemplary models in one embodiment: FIG. **6A**—depicts Lorentz and gravitational forces in x-y view; FIG. **6B**—depicts Lorentz and gravitational forces in the z-x view.

[0017] FIG. **7** depicts an exemplary model in one embodiment.

[0018] FIG. **8** depicts an exemplary model in one embodiment.

[0019] FIG. **9** depicts an exemplary model in one embodiment.

[0020] FIGS. **10A**-**10D** depict oscillations of an exemplary aluminum pot model in one aspect: FIG. **10A**—shows oscillations when the direct current is applied for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.100204; FIG. **10B**—shows oscillations when the direct current is applied for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.100206; FIG. **10C**—shows oscillations when the direct current is applied for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.100207; FIG. **10D**—shows oscillations when the direct current is applied for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.100208.

[0021] FIGS. **11A**-**11C** depict oscillations of an exemplary aluminum pot model in one aspect: FIG. **11A**—shows oscillations when the direct current is applied for 60 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and a=1.100205; FIG. **11B**—shows oscillations when the direct current is applied for 2×10^4 s, $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and a=1.100205; FIG. **11C**—shows oscillations when the direct current is applied for 2×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and a=1.100207.

[0022] FIGS. **12A**-**12I** depict oscillations of an exemplary aluminium pot model in one aspect: FIG. **12A**—shows oscillations when the direct current (DC) is applied for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and alternating current (AC) with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **12B**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.15$; FIG. **12C**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.2$; FIG. **12D**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.25$; FIG. **12E**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.3$; FIG. **12F**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.35$; FIG. **12G**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.4$; FIG. **12H**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.45$; and FIG. **12I**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.5$.

[0023] FIGS. **13A**-**13C** depict oscillations of an exemplary aluminium pot model having a stability parameter a=1.1354 in one aspect: FIG. **13A**—shows oscillations when the direct current is applied (DC) for 2×10^4 s ($\beta=0$, no AC), with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz; FIG. **13B**—DC current for 2×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and AC current with $\omega_b=\pi/2$ rad/s and $\phi=0$ rad, and $\beta=0.23$; FIG. **13C**—DC current for 2×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and AC current with $\omega_b=\pi/2$ rad/s and $\phi=0$ rad, and $\beta=0.24$.

[0024] FIGS. **14A**-**14I** depict oscillations of an exemplary aluminium pot model in one aspect: FIG. **14A**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=0$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14B**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=0.7854$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14C**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=1.5708$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14D**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=2.3562$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14E**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=3.1416$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14F**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=3.927$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14G**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=4.7124$ rad/s and $\phi=0$ rad, and $\beta=0.1$; FIG. **14H**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=5.4978$ rad/s and $\phi=0$ rad, and $\beta=0.1$; and FIG. **14I**—DC current for 1×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.37559$ Hz, and a=1.1003 and AC current with $\omega_b=6.2832$ rad/s and $\phi=0$ rad, and $\beta=0.1$.

[0025] FIGS. **15A**-**15C** depict oscillations of an exemplary aluminium pot model having a stability parameter a=1.1354 in one aspect: FIG. **15A**—DC current for 2×10^4 s ($\beta=0$ and $\omega_b=0$ rad/s, no AC), with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz; FIG. **15B**—DC current for 2×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and AC current with $\omega_b=0.3$ rad/s, and $\phi=0$ rad, and $\beta=0.23$; FIG. **15C**—DC current for 2×10^4 s, with $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz, and AC current with $\omega_b=0.5$ rad/s, and $\phi=0$ rad, and $\beta=0.23$.

[0026] FIG. **16** depicts a graph of the oscillations in an exemplary aluminum pot model for a different combination of β and ω_b at a stability parameter a=1.1354 (DC current only: $\omega_b=0$ rad/s and $\beta=0$, and $\omega_x=1.5302$ Hz and $\omega_y=0.3756$ Hz.

[0027] FIG. **17** depicts simulated deviation from the average interface.

[0028] FIGS. **18A**-**18H** depict a simulated resonant instability. FIGS. **18A**-**18D** depict an interface deformation that evolves as a circulating wave. FIG. **18E** depicts a root-mean-square displacement from the average interface shape, as it varies over time. The times plotted in a-d are marked with dots. An exponential fit is plotted as a solid line. FIG. **18F** depicts the spectral power C_{nm} for all modes, with the (n;m)=(2; 0) and (0; 1) modes the strongest. FIG. **18G** depicts a time evolution of the strengths of the (n;m)=(2; 0), (0; 1), and (0; 2) modes. FIG. **18H** depicts the spectral power of the RMS displacement, compared to frequencies of a few gravity-wave modes, known from theory.

[0029] FIGS. **19**A-**19**H depict a simulation showing preventing the resonant instability by adding an oscillatory component to the electrical current. FIGS. **19**A-**19**D depict an interface deformation that evolves as a standing wave. FIG. **19**E depicts a root-mean-square displacement from the average interface shape, as it varies over time. The times plotted in a-d are marked with dots. FIG. **19**F depicts the spectral power C_{nm} for all modes with the (n;m)=(2; 0) and (0; 1) modes the strongest. FIG. **19**G depicts a time evolution of the strengths of the (n;m)=(2; 0), (0; 1), and (0; 2) modes. FIG. **19**H depicts the spectral power of the RMS displacement, compared to frequencies of a few gravity-wave modes, known from theory.

DETAILED DESCRIPTION

[0030] The present invention can be understood more readily by reference to the following detailed description, examples, drawings, and claims, and their previous and following description. However, before the present articles, systems, and/or methods are disclosed and described, it is to be understood that this invention is not limited to the specific or exemplary aspects of articles, systems, and/or methods disclosed unless otherwise specified, as such can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting.

[0031] The following description of the invention is provided as an enabling teaching of the invention in its best, currently known aspect. To this end, those skilled in the relevant art will recognize and appreciate that many changes can be made to the various aspects of the invention described herein while still obtaining the beneficial results of the present invention. It will also be apparent that some of the desired benefits of the present invention can be obtained by selecting some of the features of the present invention without utilizing other features. Accordingly, those of ordinary skill in the pertinent art will recognize that many modifications and adaptations to the present invention are possible and may even be desirable in certain circumstances and are a part of the present invention. Thus, the following description is again provided as illustrative of the principles of the present invention and not in limitation thereof.

Definitions

[0032] As used herein, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to a "device" includes aspects having two or more such devices unless the context clearly indicates otherwise.

[0033] Ranges can be expressed herein as from "about" one particular value and/or to "about" another particular value. When such a range is expressed, another aspect includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another aspect. It should be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint.

[0034] As used herein, the terms "optional" or "optionally" mean that the subsequently described event or circumstance may or may not occur, and that the description includes instances where said event or circumstance occurs and instances where it does not.

[0035] It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting. As used in the specification and in the claims, the term "comprising" can include the aspects "consisting of" and "consisting essentially of."

[0036] For the terms "for example" and "such as," and grammatical equivalences thereof, the phrase "and without limitation" is understood to follow unless explicitly stated otherwise.

[0037] As used herein, the term "substantially," in, for example, the context "substantially no change" refers to a phenomenon or an event that exhibits less than about 1% change, e.g., less than about 0.5%, less than about 0.1%, less than about 0.05%, or less than about 0.01% change. For example, when the term substantially no change is used in the context of substantially no change is observed in the oscillations of the molten electrolyte, it is understood that the change in the oscillations is less than about 1%, less than about 0.5%, less than about 0.1%, less than about 0.05%, or less than about 0.01%.

[0038] As used herein, the term "substantially," in, for example, the context "substantially identical" or "substantially similar" refers to a method or a system, or a component that is at least about 80%, at least about 85%, at least about 90%, at least about 91%, at least about 92%, at least about 93%, at least about 94%, at least about 95%, at least about 96%, at least about 97%, at least about 98%, at least about 99%, or about 100% by similar to the method, system, or the component it is compared to.

[0039] As used herein, the terms "substantially identical reference system" or "substantially identical reference method" refer to a reference system or method comprising substantially identical components or method steps in the absence of an inventive component or a method step. In another exemplary embodiment, the term "substantially," in, for example, the context "substantially identical reference systems," refers to a reference system or a method step that comprises substantially identical components or method steps, and wherein an inventive component or a method step is substituted with a common in the art component or a method step. For example, the term substantially identical reference system without the presence of AC refers to the system that has the same components with the exception of the device configured to provide an alternating current. In yet another example, the term substantially identical reference system without the presence of AC refers to the system that has the same components with the alternating current present in the system.

[0040] As used herein, the term or phrase "parametric instability" refers to a violent undesired motion that results from the variation of a parameter whose values the system's energy depends on.

[0041] As used herein, the term "traveling wave" can be defined mathematically as a surface motion in which the deformation of the surface depends on position x and time t only in the combination $k \cdot x \pm \omega t$, where k is the wave vector, and ω is the angular frequency. In still further aspects, the term "standing wave" can be defined as a surface motion produced by the superposition of two traveling waves, one with dependence $k \cdot x + \omega t$, and one with dependence $k \cdot x - \omega t$.

[0042] The term “traveling wave” can also be referred to as a surface motion in which peaks and troughs (local maxima and minima of surface height) move as if they were traveling smoothly from place to place; while the term “standing wave” can be defined as a surface motion in which peaks and troughs change over time by growing and shrinking in place, without traveling from place to place.

[0043] Numerous other general purpose or special purpose computing devices environments or configurations can be used. Examples of well-known computing devices, environments, and/or configurations that can be suitable for use include, but are not limited to, personal computers, server computers, handheld or laptop devices, smartphones, multiprocessor systems, microprocessor-based systems, network personal computers (PCs), minicomputers, mainframe computers, embedded systems, distributed computing environments that include any of the above systems or devices, and the like.

[0044] Computing processors or devices, as disclosed herein, can contain communication connection(s) that allow the device to communicate with other devices. Computing devices can also have input device(s) such as a keyboard, mouse, pen, voice input device, touch input device, etc. Output device(s) such as a display, speakers, printer, etc., can also be included. All these devices are well known in the art and need not be discussed at length here.

[0045] Computer-executable instructions, such as program modules being executed by a computer, can be used. Generally, program modules include routines, programs, objects, components, data structures, etc., that perform particular tasks or implement particular abstract data types. Distributed computing environments can be used where tasks are performed by remote processing devices that are linked through a communications network or other data transmission medium. In a distributed computing environment, program modules and other data can be located in both local and remote computer storage media, including memory storage devices.

[0046] In its most basic configuration, a computing device typically includes at least one processing unit and memory. Depending on the exact configuration and type of computing device, memory can be volatile (such as random-access memory (RAM)), non-volatile (such as read-only memory (ROM), flash memory, etc.), or some combination of the two.

[0047] Computing devices can have additional features/functionality. For example, a computing device can include additional storage (removable and/or non-removable) including, but not limited to, magnetic or optical disks or tape.

[0048] Computing device typically includes a variety of computer-readable media. Computer-readable media can be any available media that can be accessed by the device and includes both volatile and non-volatile media, removable and non-removable media.

[0049] Computer storage media include volatile and non-volatile, and removable and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules or other data. Memory, removable storage, and non-removable storage are all examples of computer storage media. Computer storage media include, but are not limited to, RAM, ROM, electrically erasable program read-only memory (EEPROM), flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by a computing device. Any such computer storage media can be part of a computing device.

[0050] As disclosed herein, computing devices can contain communication connection(s) that allow the device to communicate with other devices. The connection can be wireless or wired. Computing devices can also have input device(s) such as a keyboard, mouse, pen, voice input device, touch input device, etc. Output device(s) such as a display, speakers, printer, etc., can also be included. All these devices are well known in the art and need not be discussed at length here.

[0051] It should be understood that the various techniques described herein can be implemented in connection with hardware components or software components or, where appropriate, with a combination of both. Illustrative types of hardware components that can be used include Field-programmable Gate Arrays (FPGAs), Application-specific Integrated Circuits (ASICs), Application-specific Standard Products (ASSPs), System-on-a-chip systems (SOCs), Complex Programmable Logic Devices (CPLDs), etc. The methods and apparatus of the presently disclosed subject matter, or certain aspects or portions thereof, can take the form of program code (i.e., instructions) embodied in tangible media, such as CD-ROMs, hard drives, or any other machine-readable storage medium where, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the presently disclosed subject matter. In yet other aspects, the software can comprise any simulation software that can be used or applied for electrolytic cells. For example, it can comprise MHD-VALDIS simulation software. However, this simulation software is only optional, exemplary and non-limiting.

[0052] While aspects of the present invention can be described and claimed in a particular statutory class, such as the system statutory class, this is for convenience only and one of ordinary skill in the art will understand that each aspect of the present invention can be described and claimed in any statutory class. Unless otherwise expressly stated, it is in no way intended that any method or aspect set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not specifically state in the claims or descriptions that the steps are to be limited to a specific order, it is in no way intended that an order be inferred in any respect. This holds for any possible non-express basis for interpretation, including matters of logic with respect to arrangement of steps or operational flow, plain meaning derived from grammatical organization or punctuation, or the number or type of aspects described in the specification.

[0053] The present invention may be understood more readily by reference to the following detailed description of various aspects of the invention and the examples included therein and to the Figures and their previous and following description.

Methods

[0054] The present disclosure is directed to a method comprising applying an alternating current (AC) comprising an oscillatory current waveform to an electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis.

[0055] It is understood that the method disclosed herein can be applied to any electrolytic cell known in the art. Many various metals are currently produced by utilizing high capacity electrolytic cells. For example, and without limitations, the methods of the current disclosure can be applied to an aluminum electrolytic cell, iron electrolytic cell steel electrolytic cell, titanium electrolytic cell, and the like. In yet further aspects, the methods disclosed herein are applied to the aluminum electrolytic cell.

[0056] It is further understood that the specific electrolyte can be specifically chosen for the desired electrolytic cell. In some aspects, the electrolyte can be an ionic solution. Yet, in other aspects, the electrolyte can comprise ionic liquids. While in still other aspects, the electrolyte can comprise molten salts.

[0057] In yet other aspects, any molten salt electrolytes can be used. In some exemplary aspects, the molten salt electrolyte comprises cryolite. In certain aspects, cryolite is a naturally occurring mineral comprising Na_2NaAlF_6. In yet other aspects, the cryolite is synthetically produced. Cryolite is known to dissolve alumina oxide. In yet further aspects, the molten salt electrolyte can further comprise aluminum fluoride, alumina, or a combination thereof. In yet further aspects, lithium fluoride and magnesium fluoride can be added in the form of lithium carbonate and magnesium oxide to form the molten salt electrolyte. It is understood that in aspects where lithium fluoride is present, lithium fluoride can participate in lowering the melting point of the salt electrolyte, decreasing the vapor pressure, density, reduced species solubility and viscosity, and it can also increase electrical conductivity.

[0058] Currently, aluminum production through electrolysis consumes about 3% of electricity worldwide (P. A. DAVIDSON and R. I. LINDSAY. Stability of interfacial waves in aluminum reduction cells. *Journal of Fluid Mechanics,* 362:273-295, 1998). In general, aluminum is produced by running large, steady (DC) electrical current through pools of molten salts atop liquid aluminum. About 40% of that energy is wasted as heat in the salt and could be saved if the salt layer were thinner. Unfortunately, thinning the salt results in a resonant instability on the interface of the salt and liquid aluminum, in which surface waves grow uncontrollably until the smelter is shutdown.

[0059] The resonant instability deforms the aluminum-salt interface in a way that changes overtime, and when the deformation becomes too large, the cell must be shut down.

[0060] It is understood that even without the presence of instability, the interface between the molten salt and liquid aluminum is not flat. Rather, it has a dome shape, caused by the combined effects of the steady electrical current and bubbles produced in aluminum's electrochemical production. Thus, such commonly used methods are energy consuming and inefficient.

[0061] In some aspects, in the methods disclosed herein, a direct current (DC) can be applied to electrolytic cell for a second predetermined time prior to applying the AC. While in other aspects, the direct current is continued to be applied for the first predetermined time simultaneously with applying the AC. It is understood that the first predetermined time can be any time needed to accomplish the desired electrolytic process. This time can be determined by the desired amount of metal to be produced by the electrolytic process, or by the amount of electrolyte present in the cell, or by the maintenance requirements of the electrolytic cell

[0062] In some aspects, the predetermined period of time can be any time period required to achieve a desirable result. In certain aspects, the predetermined period of time can be from about 1 sec to about 72 h, including exemplary values of about 20 sec, about 60 sec, about 5 min, about 10 min, about 30 min, about 1 h, about 5 h, about 10 h, about 15 h, about 20 h, about 24 h, about 30 h, about 36 h, about 42 h, about 48 h, about 54 h, about 60 h, about 66 h, and about 70 h. In yet further aspects, the electrolytic cell can exhibit substantially no change in the oscillations present in the molten salt during the electrolysis when the AC is provided.

[0063] In still further aspects, when the AC is not provided to the cell simultaneously with the DC, the DC can be applied to the cell for the second predetermined time, before the AC is applied. This second predetermined time can be defined by a time period measured from applying the DC to an appearance of a resonant instability in the electrolytic cell. It is understood that in such aspects, when the resonant instability appears in the electrolytic cell, the addition of the AC according to the methods disclosed herein stabilizes the cell, and the cell can operate as long as desired.

[0064] The electrolytic cell used in the methods disclosed herein can further comprise an anode and a cathode. It is understood that any known in the art anodes and cathodes can be utilized depending on the specific electrolytic cell. In certain aspects, the anode and/or cathode can comprise carbon.

[0065] In the methods disclosed herein, the AC properties such as the amplitude, frequency and/or phase can be predetermined such that an anode-to-cathode distance is reduced when it is compared to an anode-to-cathode distance (ACD) of a substantially identical reference electrolytic cell in the absence of applying an AC. As shown in the Examples below, the conventional electrolytic cell, in the absence of the AC, can operate without sufficient instability when the ACD is not smaller than 4.2 cm. Any attempts to decrease this distance in the conventional cells can result in the appearance of instability and rendering the electrolytic cell un-operational.

[0066] The methods disclosed herein allow reduction of the ACD value while keeping the electrolytic cell stable with substantially no change in the current oscillation during the electrolysis.

[0067] It is understood that in some aspects, the methods disclosed herein allow to obtain an electrolytic cell that exhibits an increase in the energy efficiency when is compared to the energy efficiency of a substantially identical reference electrolytic cell in the absence of applying the AC. In certain aspects, the electrolytic cell exhibits an increase in energy efficiency that is substantially proportional to a reduction in the anode-to-cathode distance. In some exemplary and unlimiting aspects, if the ACD is reduced by about 5%, the energy efficiency can be increased by about 5%.

[0068] In still further aspects, the methods disclosed herein allow the electrolytic cell to exhibit an increase in the energy efficiency of at least about 5%, at least about 7%, at least about 10%, at least about 12%, or at least about 14%

when compared to the substantially identical reference electrolytic cell in the absence of applying an AC.

[0069] In still further aspects, the AC has a waveform that is defined by a plurality of modes. In such aspects, the combination of the plurality of modes can result in the formation of a standing wave. In still further aspects, the plurality of modes of the waveform are configured to disrupt the formation and/or growth of circulating waves that are responsible for the electrolytic cell instability.

[0070] In certain aspects, the oscillatory current waveform can comprise any shape. In some exemplary and unlimiting aspects, the oscillatory current waveform can comprise a sinusoidal, cosinusoidal, triangular, or square shape.

[0071] In certain aspects, the AC can be provided by any known in the art methods. In some aspects, the AC can be provided by a device comprising an alternating current source that is in electrical communication with the electrolytic cell. Any known in the art AC devices can be utilized. In some exemplary and unlimiting aspects, the device can comprise solid-state components, mechanical components, or any other components capable of providing an alternating current. As disclosed in detail above, the device can generate an AC oscillatory current waveform defined by the desired predetermined amplitude, frequency, and/or phase.

[0072] In yet other aspects, and as described above, the DC can also be provided by any known in the art sources. In some aspects, the DC is provided by the same device that is providing the AC. In such aspects, in addition to the alternating current source, the device can comprise a direct current source. In yet other aspects, the DC can be provided by a separate direct current source. It is understood that any of the DC sources can provide DC having the desired amplitude and in an amount needed to imitate the electrolytic reaction.

[0073] In still further aspects, it is understood that the predetermined amplitude of the DC can be chosen based on the specific parameters of the electrolytic cell and the desired results. In certain aspects, the predetermined amplitude of the DC has an amplitude effective to initiate electrolysis. In yet further aspects, the predetermined amplitude of the direct current can have values from about 100 kA to about 500 kA, including exemplary values of about 120 kA, about 150 kA, about 180 kA, about 200 kA, about 220 kA, about 250 kA, about 280 kA, about 300 kA, about 320 kA, about 350 kA, about 380 kA, about 400 kA, about 420 kA, about 450 kA, and about 480 kA. It is further understood that any value between any two foregoing values can be used for the direct current.

[0074] In still further aspects, the predetermined amplitude, frequency, and/or phase of the AC can be chosen based on the specific parameters of the cell. In yet other aspects, it can be selected such that the electrolytic cell having the AC applied to exhibit no substantial oscillations in the molten electrolyte during the electrolysis.

[0075] In certain aspects, the predetermined amplitude of the AC can have values from about 0.5 kA to about 50 kA, including exemplary values of about 1 kA, about 1.5 kA, about 2 kA, about 2.5 kA, about 3 kA, about 3.5 kA, about 4 kA, about 4.5 kA, about 5 kA, about 5.5 kA, about 6 kA, about 6.5 kA, about 7 kA, about 7.5 kA, about 8 kA, about 8.5 kA, about 9 kA, about 9.5 kA, about 10 kA, about 12 kA, about 15 kA, about 17 kA, about 20 kA, about 22 kA, about 25 kA, about 27 kA, about 30 kA, about 32 kA, about 35 kA, about 37 kA, about 40 kA, and about 42 kA, about 45 kA, and about 47 kA. It is further understood that any value between any two foregoing values can be used for the AC

[0076] In yet further aspects, the AC can be further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, wherein the β is from greater than 0 to about 1, including an exemplary value of about 0.1, about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, and about 0.9. Yet, in other aspects, the β is from greater than 0 to about 0.15, including exemplary value of about 0.05, about 0.07, about 0.1, about 0.11, about 0.12, about 0.13, and about 0.14. It is understood that the non-dimensional amplitude ratio β can have any value between any two foregoing values.

[0077] In still further aspects, the predetermined frequency of the AC can be from greater than 0 to about π rad/s, including exemplary values of about π/50 rad/s, about π/40 rad/s, about π/30 rad/s, about π/20 rad/s, about π/10 rad/s, and π/5 rad/s. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0078] In still further aspects, the predetermined frequency of the AC can be from greater than 0 Hz to about 0.5 Hz, including exemplary values of about 0.01 Hz, about 0.02 Hz, about 0.03 Hz, about 0.04 Hz, about 0.05 Hz, about 0.06 Hz, about 0.07 Hz, about 0.08 Hz, about 0.09 Hz, about 0.1 Hz, about 0.15 Hz, about 0.2 Hz, about 0.25 Hz, about 0.3 Hz, about 0.35 Hz, about 0.4 Hz, and about 0.45 Hz. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0079] In still further aspects, the predetermined frequency of the AC can also be from greater than 0 to about 120π rad/s, including exemplary values of about 1/3π rad/s, about 1/2π rad/s, about 3/4π rad/s, about π rad/s, about 3π/2 rad/s, about 2π rad/s, about 3π rad/s, about 4π rad/s, about 5π rad/s, about 10π rad/s, about 15π rad/s, about 20π rad/s, about 25π rad/s, about 30π rad/s, about 35π rad/s, about 40π rad/s, about 45π rad/s, about 50π rad/s, about 55π rad/s, about 60π rad/s, about 65π rad/s, about 70π rad/s, about 75π rad/s, about 80π rad/s, about 85π rad/s, about 90π rad/s, about 95π rad/s, about 100 π rad/s, about 105π rad/s, about 110π rad/s, and about 115π rad/s. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0080] In still further aspects, the predetermined frequency of the AC can be from greater than 0 Hz to about 60 Hz, including exemplary values of about 0.1 Hz, about 0.5 Hz, about 1 Hz, about 2 Hz, about 5 Hz, about 10 Hz, about 20 Hz, about 30 Hz, about 40 Hz, and about 50 Hz. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0081] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 0.15, including exemplary values of about 0.05, about 0.07, about 0.1, about 0.11, about 0.12, about 0.13, and about 0.14; and the predetermined frequency values from greater than 0 to about π rad/s, including exemplary values of about π/50 rad/s, about π/40 rad/s, about π/30 rad/s, about π/20 rad/s, about π/10 rad/s, and π/5 rad/s. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0082] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 0.15, including exemplary values of about 0.05, about 0.07, about 0.1, about 0.11, about 0.12, about 0.13, and about 0.14; and the predetermined frequency values from greater than 0 to about 0.5 Hz, including exemplary values of about 0.01 Hz, about 0.02 Hz, about 0.03 Hz, about 0.04 Hz, about 0.05 Hz, about 0.06 Hz, about 0.07 Hz, about 0.08 Hz, about 0.09 Hz, about 0.1 Hz, about 0.15 Hz, about 0.2 Hz, about 0.25 Hz, about 0.3 Hz, about 0.35 Hz, about 0.4 Hz, and about 0.45 Hz. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0083] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 1, about 0.1, including exemplary values of about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, and about 0.9; and the predetermined frequency values from greater than 0 to about 120n rad/s, including exemplary values of about 1/3π rad/s, about 1/2π rad/s, about 3/4π rad/s, about π rad/s, about 3π/2 rad/s, about 2π rad/s, about 3π rad/s, about 4π rad/s, about 5π rad/s, about 10π rad/s, about 15π rad/s, about 20π rad/s, about 25π rad/s, about 30π rad/s, about 35π rad/s, about 40π rad/s, about 45π rad/s, about 50π rad/s, about 55π rad/s, about 60π rad/s, about 65π rad/s, about 70π rad/s, about 75π rad/s, about 80π rad/s, about 85π rad/s, about 90π rad/s, about 95π rad/s, about 100 π rad/s, about 105π rad/s, about 110π rad/s, and about 115π rad/s. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0084] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 1, about 0.1, including exemplary values of about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, and about 0.9; and the predetermined frequency values from greater than 0 to about 60 Hz, including exemplary values of about 0.1 Hz, about 0.5 Hz, about 1 Hz, about 2 Hz, about 5 Hz, about 10 Hz, about 20 Hz, about 30 Hz, about 40 Hz, and about 50 Hz. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0085] It is further understood that the standing waves can be affected by the viscosity and/or surface tension of the electrolyte, and therefore these parameters need to be taken into consideration when the AC parameters are chosen for the specific cell.

[0086] In still further aspects, the methods disclosed herein allow substantially no change in oscillations to be present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell. In such aspects, the methods disclosed herein allow to reduce the anode-to-cathode distance relative to the conventional methods. In some aspects, the anode-to-cathode distance is also equivalent to the thickness of the electrolyte layer. In such exemplary aspects, the anode-to-cathode distance or the thickness of the electrolyte can be equal to or less than about 4.5 cm, less than about 4.3 cm, less than about 4.2 cm, less than about 4 cm, less than about 3.8 cm, less than about 3.5 cm, less than about 3.3 cm, less than about 3 cm, less than about 2.8 cm, less than about 2.5 cm, or less than about 2 cm. In still further aspects, the thickness of the electrolyte or the anode-to-cathode distance can be anywhere between about 3 cm to about 4.3 cm, including exemplary values of about 3.1 cm, about 3.2 cm, about 3.3 cm, about 3.4 cm, about 3.5 cm, about 3.6 cm, about 3.7 cm, about 3.8 cm, about 3.9 cm, about 4.0 cm, about 4.1 cm, and about 4.2 cm.

[0087] In still further aspects, the methods disclosed herein comprise a step of measuring the current oscillations. It is understood that the step of measuring can be performed by any known in the art methods. In some exemplary aspects, the measuring can be performed with by a controlling unit that is in a feedback loop communication with the device and the electrolytic cell such that it is configured to receive an input communication comprising a first data from the device and/or the electrolytic cell and provide an output communication to the device and/or the electrolytic cell, wherein the output communication comprises a second data adjusted for the first data.

[0088] In such an aspect, the controlling unit collects and records the first data, wherein the first data can comprise physical and electrical parameters of the cell. The signal obtained from the cell and/or device is evaluated. The controlling unit then can communicate to the device and/or the electrolytic cell the second data that is adjusted for the specific cell/device parameters to obtain the desired properties. In such aspects, the second data can comprise the predetermined amplitude, frequency, and/or phase, or β of AC based on the feedback communication from the electrolytic cell and/or device. In still further aspects, the device is also in a feedback loop communication with the electrolytic cell.

[0089] In yet further aspects, the methods disclosed herein comprise a step of adjusting the predetermined amplitude, frequency, and/or phase, or β of AC based on the feedback communication from the electrolytic cell.

[0090] It is understood that the data collection, its analysis and adjustment can be performed by a computing processor or a computing device. For example, the controlling unit can comprise a computing processor. Yet, in other examples, both or either the electrolytic cell and device can comprise a computing processor. In still further aspects, the controlling unit, device, and electrolytic cell can be in communication with the same computing processor. Any known in the art computing processors capable of the desired task can be used. In still further aspects, the data communicated to the computing processor can be provided by any means, including wireless communication, wired communication, through intermediate media such as a flash drive, a CD-ROM or a DVD.

[0091] In still further aspects, the controlling unit can also comprise a measuring unit that is configured to measure the specific output of the electrolytic cell or that of the device. In such aspects, the measuring unit can be configured, for example, to measure an electrical response from the cell and can comprise ultrasound probes, laser range finders, capacitive probes, and the like.

[0092] Also disclosed herein is a method comprising: a) providing a first data to a computational processor, wherein the first data comprises at least one of one or more of geometric parameters of an electrolytic cell, a cathode-to-anode-distance of the electrolytic cell, a value of a direct current; an amplitude of a direct current, a thickness of a metal layer, material properties of a metal, material properties of an electrolyte, material properties of a cathode, material properties of an anode, or any combination thereof; b) analyzing the first data by the computational processor to provide a second data comprising parameters of an alternating current (AC) wherein the parameters comprise one or more of a first amplitude, a first frequency, and/or a first phase of an oscillatory current form of the AC; and c) applying the AC having one or more parameters present in the second data to the electrolytic cell to stabilize the electrolytic cell.

[0093] In still further aspects, the methods can further comprise d) collecting a third data from the electrolytic cell and transferring the third data to the computational processor to analyze the performance of the electrolytic cell; e) analyzing the third data by the computational processor to provide a fourth data comprising parameters of the alternating current (AC) wherein the parameters comprise one or more of a second amplitude, a second frequency, and/or a second phase of an oscillatory current form of the AC; and f) applying the AC having one or more parameters present in the fourth data to the electrolytic cell.

[0094] It is understood that in such aspects, the first data can comprise any data that relates to a specific electrolytic cell. The methods disclosed herein can be used to provide tuned AC parameters as a function of the parameters of the specific electrolytic cell. It is also understood that any of the mentioned above parameters can be used. In some aspects, all of the above parameters can be provided to the computational processor for analysis and determination of the specific AC parameters.

[0095] In still further aspects, after the computational processor provides the second data with the desired AC parameters, the AC is applied to the electrolytic cell. The electrolytic cell is then monitored, for example, for stability and/or energy performance, the third data from the electrolytic cell can be transferred back to the computational processor for analysis of the cell performance. If needed, the AC parameters can be adjusted if needed, and a new AC having adjusted parameters can be applied to the electrolytic cell. It is further understood that the steps of receiving the data from the electrolytic cell, analyzing it and providing adjusted parameters for AC to be applied to the electrolytic cell can be repeated as many times as needed to ensure that the electrolytic cell is stabilized such that substantially no change in a current oscillation is observed in an electrolyte during electrolysis.

[0096] It is also understood that in the aspects where DC is provided prior to the applying AC, the computational processor can also include this data in addition to any other data mentioned above and provide the operator with timing when the AC should be applied to the cell.

[0097] Also disclosed herein are the methods for increasing energy efficiency in an electrolytic cell. In such aspects, the methods can comprise applying an alternating current (AC) comprising an oscillatory current waveform to the electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis; wherein the energy efficiency is increased by at least about 5% when compared to a substantially identical reference electrolytic cell in the absence of applying an AC. In such aspects, the energy efficiency can also be increased by at least about 7%, at least about 8%, at least about 9%, at least about 10%, at least about 11%, at least about 12%, at least about 13%, at least about 14%, at least about 15%, at least about 16%, at least about 17%, at least about 18%, at least about 19%, or even at least about 20% when compared to a substantially identical reference electrolytic cell in the absence of applying an AC.

Systems

[0098] In some aspects described herein is a system comprising: a) an electrolytic cell comprising: i) an anode; ii) a cathode; and iii) a molten electrolyte having a predetermined thickness; b) a direct current source that is in electrical communication with the electrolytic cell and is configured to provide a direct current (DC) having a predetermined amplitude and to initiate an electrolysis reaction in the electrolytic cell; c) a device comprising an alternating current source (AC); wherein the device is in electrical communication with the electrolytic cell and is configured to provide an alternating current (AC) to the electrolytic cell, wherein the AC comprises an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase; and wherein the device is in feedback loop communication with the electrolytic cell; and wherein the electrolytic cell exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell.

[0099] It is understood that any of the electrolytic cells mentioned above can be utilized. In still further exemplary aspects, the disclosed electrolytic cell is an aluminum electrolysis cell. In such cells, the molten salt electrolyte can comprise cryolite.

[0100] In still further exemplary aspects, the anode comprises a carbon. In yet other aspects, the cathode comprises a carbon. In still further aspects, both anode and cathode comprise carbon blocks.

[0101] An exemplary and unlimiting aluminum production cell is shown in FIG. **1**. Aluminum is produced using Hall-Heroult cells (H-H cells) **100**, which has two large carbon blocks that serve as electrodes (an anode (**102**) on the top of the cell and cathode (**104**) at the bottom) with two liquid layer in between (aluminum (**108**) at the bottom, electrolyte on top (**106**)) (UC RUSAL. How aluminium is produced, 2019). H-H cells utilize an electrochemical process known as electrolysis. Electrolysis uses electrical currents to separate elements from naturally occurring ores. In the Hall-Heroult process, naturally occurring alumina (aluminum oxide) is first dissolved in a bath of molten electrolyte (cryolite). Applying a direct electrical current (DC), typically greater than 300 kA, decomposes the naturally occurring alumina into aluminum metal (deposited at the cathode) and carbon dioxide gas (produced at the anode) (UC RUSAL. How aluminium is produced, 2019)

[0102] However, only about 60% is consumed for that purpose as the remaining 40% becomes heat through a process known as Joule heating (resistive heating) (P. A. Davidson. Overcoming instabilities in aluminium reduction cells: a route to cheaper aluminium. *Materials Science and Technology,* 2000). Joule heating is caused by electrons from the supplied current interacting with the atoms of the conducting material and scales as the supplied current (J) squared multiplied by the electrical resistance (R) of the conducting material. The resistance R depends on a material property known as electrical resistivity. For the H-H cell, the molten cryolite layer has an electrical resistivity 100 times bigger than that of the carbon blocks and 10,000 times bigger than that of the molten aluminum layer, making it the dominant source of electrical energy lost to heat. Without wishing to be bound by any theory, it is hypothesized that a decrease in the height of the electrolyte layer can result in reduced energy loss. However, currently, when the height of the molten electrolyte layer is reduced below a threshold of around 4.5 cm, the molten layers inside the cell slosh violently, sloshing back and forth, which can result in the aluminum layer touching the carbon anode at the top, and therefore, in failure to electrolyze alumina.

[0103] This sloshing is an example of parametric instability. In the case of the sloshing instability, small gravity-restored waves at the interface (**110**) between the aluminum and cryolite layers, which occur naturally, are amplified strongly by the electrical current in a feed-forward process. The difference in resistivity between the two layers draws more current into regions where the cryolite is thin and less into regions where it is thick. Without wishing to be bound by any theory, it is assumed that this will result in a compensating horizontal current in the aluminum layer that interacts with vertical magnetic fields from nearby cells to produce forces that make the thin regions thinner and the thick regions thicker (P. A. DAVIDSON and R. I. LINDSAY. Stability of interfacial waves in aluminium reduction cells. *Journal of Fluid Mechanics,* 362:273-295, 1998). More current is drawn into thin regions, and the cycle repeats. It is understood that existing technology does not allow a reduction of the molten electrolyte layer below ~4.5 cm, as such a reduction renders an H-H cell unstable.

[0104] In certain aspects, and as disclosed herein, to improve the stability of the H-H cell and to minimize parametric instability, the disclosed system comprises an oscillatory (AC) component added to the electrical current.

[0105] In further aspects, and as disclosed herein, the system comprises a device comprising an alternating current source; wherein the device is in electrical communication with the electrolytic cell and is configured to provide an alternating current (AC) to the electrolytic cell, wherein the AC comprises an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase. In yet other aspects, the direct current source that is in electrical communication with the electrolytic cell and configured to provide a direct current (DC) having a predetermined amplitude and to initiate an electrolysis reaction in the electrolytic cell is present in the same device, as the AC source. However, in other aspects, the DC source can be present in a separate device.

[0106] In still further aspects, the system can further comprise a controlling unit configured to measure oscillations of the molten salt electrolyte as a function of the DC and AC applied to the electrolytic cell, and wherein the controlling unit is in a feedback loop communication with the device and the electrolytic cell.

[0107] FIG. **2** shows an exemplary system **200** that comprises an aluminum pot (**202**) that is in electrical communication with the device **204**. In this exemplary aspect, the device **204** comprises both AC and DC sources. The AC and DC are provided to the aluminum pot **202** by the electrical connection **201**. The electrical response of the cell is measured (**203**) by a measuring unit (**206**). The response can then be fed back (**205**) to the device **204** to adjust the current parameters based on the desired outcome.

[0108] FIG. **3** shows an exemplary system **300** in another aspect. In such an aspect, the system can comprise an aluminum pot (**302**) that is in electrical communication with the device **308** that is configured to provide a direct current and the device **304** that is configured to provide an alternating current. The electrical response of the cell **302** is measured (**303**) by a measuring unit (**306**). The response can then be fed back (**305**) to the device **304** to adjust the current parameters based on the desired outcome.

[0109] In certain aspects, the measuring unit is configured to measure an electrical response from the cell and can comprise ultrasound probes, laser range finders, capacitive probes, and the like. In still further aspects, the measuring unit can be a part of the controlling unit. In yet other aspects, the controlling unit can also comprise a measuring unit that is in communication with the device and/or electrolytic cell.

[0110] In still further aspects, the electrolytic cell of the disclosed system exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell. In yet other aspects, no change in oscillations present in the molten salt electrolyte can be observed for the cell where the predetermined thickness of the molten electrolyte is equal to or less than about 4.5 cm, less than about 4.3 cm, less than about 4.2 cm, less than about 4 cm, less than about 3.8 cm, less than about 3.5 cm, less than about 3.3 cm, less than about 3 cm, less than about 2.8 cm, less than about 2.5 cm, or less than about 2 cm. In still further aspects, the thickness of the electrolyte is between about 3 cm to about 4.3 cm, including exemplary values of about 3.1 cm, about 3.2 cm, about 3.3 cm, about 3.4 cm, about 3.5 cm, about 3.6 cm, about 3.7 cm, about 3.8 cm, about 3.9 cm, about 4.0 cm, about 4.1 cm, and about 4.2 cm. In yet other aspects, the predetermined thickness of the electrolyte is substantially identical to an anode-to-cathode-distance, as disclosed above.

[0111] In still further aspects, the disclosed systems allow a reduction in the anode-to-cathode distance. In such aspects, the amplitude, frequency and/or phase of the AC are predetermined such that an anode-to-cathode distance is reduced when it is compared to an anode-to-cathode distance of a substantially identical reference electrolytic cell in the absence of providing the AC.

[0112] In still further unlimiting aspects, the oscillatory current waveform of AC can comprise a sinusoidal, cosinusoidal, triangular, or square shape. It is understood that the shape, normalized amplitude, normalized frequency, and/or phase could also change over time, for example, in response to feedback. In yet further aspects, the waveform is defined by a plurality of modes forming a standing wave. These standing waves are configured to disrupt a formation and growth of circulating waves, as disclosed herein.

[0113] In yet further aspects, the AC can be further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, wherein the β is from greater than 0 to about 1, including exemplary value of about 0.1, about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, and about 0.9. Yet, in other aspects, the β is from greater than 0 to about 0.15, including exemplary value of about 0.05, about 0.07, about 0.1, about 0.11, about 0.12, about 0.13, and about 0.14. It is understood that the non-dimensional amplitude ratio β can have any value between any two foregoing values.

[0114] In still further aspects, the predetermined frequency of the AC can be from greater than 0 to about π rad/s, including exemplary values of about $\pi/50$ rad/s, about $\pi/40$ rad/s, about $\pi/30$ rad/s, about $\pi/20$ rad/s, about $\pi/10$ rad/s, and $\pi/5$ rad/s. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0115] In still further aspects, the predetermined frequency of the AC can be from greater than 0 Hz to about 0.5 Hz, including exemplary values of about 0.01 Hz, about 0.02 Hz, about 0.03 Hz, about 0.04 Hz, about 0.05 Hz, about 0.06 Hz, about 0.07 Hz, about 0.08 Hz, about 0.09 Hz, about 0.1 Hz, about 0.15 Hz, about 0.2 Hz, about 0.25 Hz, about 0.3 Hz, about 0.35 Hz, about 0.4 Hz, and about 0.45 Hz. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0116] In still further aspects, the predetermined frequency of the AC can also be from greater than 0 to about 120π rad/s, including exemplary values of about 1/3π rad/s, about 1/2π rad/s, about 3/4π rad/s, about π rad/s, about 3π/2 rad/s, about 2π rad/s, about 3π rad/s, about 4π rad/s, about 5π rad/s, about 10π rad/s, about 15π rad/s, about 20π rad/s, about 25π rad/s, about 30π rad/s, about 35π rad/s, about 40π rad/s, about 45π rad/s, about 50π rad/s, about 55π rad/s, about 60π rad/s, about 65π rad/s, about 70π rad/s, about 75π rad/s, about 80π rad/s, about 85π rad/s, about 90π rad/s, about 95π rad/s, about 100π rad/s, about 105π rad/s, about 110π rad/s, and about 115π rad/s. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0117] In still further aspects, the predetermined frequency of the AC can be from greater than 0 Hz to about 60 Hz, including exemplary values of about 0.1 Hz, about 0.5 Hz, about 1 Hz, about 2 Hz, about 5 Hz, about 10 Hz, about 20 Hz, about 30 Hz, about 40 Hz, and about 50 Hz. It is understood that the predetermined frequency of the AC can have any value between any two foregoing values.

[0118] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 0.15, including exemplary values of about 0.05, about 0.07, about 0.1, about 0.11, about 0.12, about 0.13, and about 0.14; and the predetermined frequency values from greater than 0 to about π rad/s, including exemplary values of about π/50 rad/s, about π/40 rad/s, about π/30 rad/s, about π/20 rad/s, about π/10 rad/s, and π/5 rad/s. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0119] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 0.15, including exemplary values of about 0.05, about 0.07, about 0.1, about 0.11, about 0.12, about 0.13, and about 0.14; and the predetermined frequency values from greater than 0 to about 0.5 Hz, including exemplary values of about 0.01 Hz, about 0.02 Hz, about 0.03 Hz, about 0.04 Hz, about 0.05 Hz, about 0.06 Hz, about 0.07 Hz, about 0.08 Hz, about 0.09 Hz, about 0.1 Hz, about 0.15 Hz, about 0.2 Hz, about 0.25 Hz, about 0.3 Hz, about 0.35 Hz, about 0.4 Hz, and about 0.45 Hz. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0120] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 1, about 0.1, including exemplary values of about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, and about 0.9; and the predetermined frequency values from greater than 0 to about 120π rad/s, including exemplary values of about 1/3π rad/s, about 1/2π rad/s, about 3/4π rad/s, about π rad/s, about 3π/2 rad/s, about 2π rad/s, about 3π rad/s, about 4π rad/s, about 5π rad/s, about 10π rad/s, about 15π rad/s, about 20π rad/s, about 25π rad/s, about 30π rad/s, about 35π rad/s, about 40π rad/s, about 45π rad/s, about 50π rad/s, about 55π rad/s, about 60π rad/s, about 65π rad/s, about 70π rad/s, about 75π rad/s, about 80π rad/s, about 85π rad/s, about 90π rad/s, about 95π rad/s, about 100π rad/s, about 105π rad/s, about 110π rad/s, and about 115π rad/s. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0121] In yet further aspects, the AC can have the predetermined β values from greater than 0 to about 1, about 0.1, including exemplary values of about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, and about 0.9; and the predetermined frequency values from greater than 0 to about 60 Hz, including exemplary values of about 0.1 Hz, about 0.5 Hz, about 1 Hz, about 2 Hz, about 5 Hz, about 10 Hz, about 20 Hz, about 30 Hz, about 40 Hz, and about 50 Hz. In still further aspects, the AC can have any β values and any frequency values between any two foregoing values.

[0122] It is understood that in some aspects, the systems disclosed herein are more energy efficient when is compared to the common systems without the presence of the AC. In certain aspects, the inventive systems exhibit an increase in the energy efficiency by at least about 5%, at least about 7%, at least about 10%, at least about 12%, or at least about 14% when compared to the substantially identical reference system in the absence of the AC. In yet other aspects, the electrolytic cell present in the disclosed system can exhibit an increase in the energy efficiency that is substantially proportional to a reduction in the anode-to-cathode distance.

EXAMPLES

[0123] The following examples are put forth so as to provide those of ordinary skill in the art with a complete disclosure and description of how the compounds, compositions, articles, devices and/or methods claimed herein are made and evaluated and are intended to be purely exemplary and are not intended to limit the disclosure. Efforts have been made to ensure accuracy with respect to numbers (e.g., amounts, temperature, etc.), but some errors and deviations should be accounted for.

Example 1

[0124] The stability of a simulated mechanical analog to the fluid layers inside the H-H cell, as shown in FIG. **1**, has been studied.

[0125] Since the liquid layers (e.g., aluminum and electrolyte) are broad and shallow, a slight tilting of the interface substantially redistributes the current density J in the cell. Furthermore, the conductivity of aluminum is much higher than that of the carbon electrodes, and therefore, excess current is drawn into the aluminum in regions where the thickness of the electrolyte is reduced, and less current is drawn at regions where the thickness of the electrolyte is increased. In other words, the resulting perturbation current density j is downwards at the wave crests and upwards at the troughs.

[0126] The perturbed current density j produces a perturbed magnetic field denoted by b. J_0 and B_0 have been chosen to define the unperturbed current density and magnetic field. Then, the perturbed Lorentz force can be defined by Eq. 1:

$$J_0 \times b + j \times B_0 \qquad \text{(Eq. 1)}$$

[0127] It was previously shown that the interface can support an infinite number of conventional standing waves in the absence of a magnetic field. The normal modes associated with these gravitational standing waves form an orthogonal set of functions. Hence, an arbitrary disturbance can be represented as a superposition of many gravitational modes. The redistribution of current caused by one gravitational mode gives rise to a perturbed Lorentz force, which can excite many other gravitational modes coupling certain modes. This coupling leads to instability involving two or more adjacent gravitational frequencies

[0128] The mechanical model described herein includes a sinusoidal component that is introduced to the unperturbed current density. The model **400** (FIG. **4**) considered herein has a compound pendulum that is made from a flat aluminum plate **404** attached to a parallel fixed surface by a pivoted rigid struct that allows the plate to freely swing about two horizontal axes (x and y). The origin of the system (O) is located at the connection between the aluminum plate and the strut. The initial cryolite layer (**402**) height is denoted by h_0, and the aluminum height by H. The aluminum plate has horizontal dimensions L_x and L_y.

[0129] A uniform current density is defined by Eq. 2 is applied to the system

$$J=J_0(1+\beta\sin(\omega_b t+\phi)) \quad \text{(Eq. 2)}$$

[0130] where J_0 is the DC, β is a non-dimensional amplitude ratio of the AC compared to that of the DC, ω_b is the angular frequency of the AC, and ϕ is its phase.

[0131] A uniform vertical magnetic field, B_z, is imposed. As described herein and shown in FIG. **4**, ρ and σ represent the density and electrical conductivity, respectively. The origin of the axes lies at the center of the electrolyte-plate interface in the unperturbed state (marked with an "O").

Example 2

[0132] To simplify the calculations, the following assumptions have been introduced. First, the characteristic time scale for the wave motion (period of oscillation) was found to be much greater than the magnetic field diffusion time. In such aspects, it was assumed that the current would immediately relax to a new equilibrium distribution each time the interface moves. Further, it was assumed that j feeding into the aluminum does not penetrate the carbon cathode block. Without wishing to be bound by any theory, it was assumed that this is due to the electrical resistivity of carbon is much higher than that of aluminum. It was further assumed that the fluid is inviscid. In such an aspect, it was assumed that the damping of high-wavenumber perturbations would not be mimicked. It was further assumed that surface tension could be ignored, and there is no background motion in the unperturbed state ($u_0=0$). This imposes a limitation on B_0 as it must satisfy Eq. 3 to ensure that the perturbations are about an equilibrium configuration:

$$\nabla\times(J_0\times B_0)=0 \quad \text{(Eq. 3)}$$

[0133] Further, the shallow water approximation was used, kh<<1, where k is a typical wavenumber. Such an assumption leads to the following simplifications: i) the perturbed current j is vertical in the electrolyte (due to the thin layer of electrolyte having the dominant resistance to the current flow forcing the current to pass directly downwards through this layer); ii) aluminum is a great conductor and assumed to be an equipotential surface (j is horizontal in the aluminum and is uniformly distributed across the plate. In other words, the perturbed current "shorts" through the aluminum); iii) the aspect ratio, kh<<1 can give rise to the fact that the perturbed current in the electrolyte is much smaller than that in the aluminum, i.e., $j_c \ll j_{Al}$ (hence, the perturbed Lorentz force acting on the electrolyte can be neglected); iv) the velocity in each layer is uniform in a z axis and a horizontal axis (it follows from the fact that the Lorentz force in the aluminum plate is independent of depth); and v) when "H" and "V" denote horizontal and vertical components respectively, $j_H\times B_H$ is vertical, and thus perturbs the vertical pressure gradient only and can be neglected. $J_V\times B_H$ is much smaller than $j_H\times B_V$ because of (ii). Also, $j_V\times B_V$ is of order kH smaller than $j_V\times B_H$. Therefore, the dominant contribution to the perturbed Lorentz force in the aluminum can be presented according to Eq. 4:

$$j_V\times B_H \text{ or } j\times(B_z\hat{e}_z) \quad \text{(Eq. 4)}$$

[0134] Further, it was assumed that the aluminum plate and electrolyte layer are thin and broad, i.e., $L_x, L_y \gg h, H$. It was also assumed, for convenience, that $B_z \gg B_x, B_y$; and that $\rho_{electrolyte} \ll \rho_{aluminium}$, which implies that the inertia of the electrolyte can be ignored.

Example 3

Derivation of Equations of Motion

Example 3.1 Boundary Conditions

[0135] For the following sections, subscripts "e" and "al" are used to denote the electrolyte and the aluminum plate, respectively. In addition, superscripts are used to denote the axis at which the system property or characteristic is considered. For example, j_e^z refers to the perturbed current density in the electrolyte along the z-direction.

[0136] Since aluminum is much more electrically conductive than the electrolyte and the carbon cathode block, it can be assumed that the current perturbations form closed loops inside of the aluminium plate (O. Zikanov. Metal pad instabilities in liquid metal batteries. *PHYSICAL REVIEW E*, 92(6), 2015). This assumption translates mathematically to the following boundary conditions (Eqs. 5-7):

$$j_{al}^x\cdot\hat{n}|_c=0=j_{al}^y\cdot\hat{n}|_c;\ \text{where } c \text{ indicates“boundary of plate”} \quad \text{(Eq. 5)}$$

$$j_{al}^z|_{z=0}=j_e^z \quad \text{(Eq. 6)}$$

$$j_{al}^z|_{z=-H}=0 \quad \text{(Eq. 7);}$$

[0137] where n̂ is a unit normal vector to the plate's boundary in the x-y plane.

Example 3.2 Change in Electrolyte Thickness Under x and y Rotations

[0138] FIG. **4** shows an exemplary model used herein. The following parameters have been defined: h(x, y) is assumed to be the local thickness of the electrolyte, and h_0 is assumed to be the equilibrium value of h. It was further assumed that a small rotation of θ_x of the plate about the x-axis is present. Further, Δh_x has been assumed to be the perpendicular distance from the top of the plate to the y-axis (see FIGS. **5**A-**5**C).

[0139] Using simple geometrical arguments, it was shown that the angle between the aluminum plate and the y-axis is θ_x. Thus, according to Eq. 8

$$\tan\theta_x = \frac{\Delta h_x}{y - h_0\sin\theta_x}. \tag{Eq. 8}$$

[0140] However, for small θ_x, $\tan\theta_x \approx \sin\theta_x = \theta_x$. Substituting this assumption into Eq. 8, it can be found that:

$$\Delta h_x \approx y\theta_x - h_0\theta_x^2 \tag{Eq. 9}$$

[0141] Similarly, if a small rotation of θ_y of the plate about the y-axis is assumed, then Δh_y is set to be the perpendicular distance between the top of the plate and the x-axis. Then, using the small-angle approximation (Eq. 10):

$$\Delta h_y \approx x\theta_y + h_0\theta_y^2 \tag{Eq. 10}$$

[0142] In such instances, a rotation of θ_x decreases the electrolyte thickness by Δh_x, while a rotation of θ_y increases the electrolyte thickness by Δh_y. Using the principle of superposition, for a combined rotation of θ_x and θ_y, the electrolyte thickness is given by (Eq. 11):

$$\begin{aligned} h(x, y) &= h_0 + \Delta h_y - \Delta h_x \\ &\approx h_0 + x\theta_x + h_0\theta_y^2 - y\theta_x + h_0\theta_x^2 \\ &\approx h_0 + x\theta_x - y\theta_x \end{aligned} \tag{11}$$

3.3 Perturbed Current Density in the Electrolyte

[0143] Since the electrical conductivity of the aluminum plate is much higher than that of the electrolyte, the aluminum plate is an equipotential surface at ϕ_0. Since the infinitesimal perturbations of the interface are much smaller than the thickness of the electrolyte and the thickness of the plate, it is assumed that ϕ_0 does not change when the interface is tilted. Using the narrow gap approximation, Φ can be found (Eq. 12):

$$\Phi = \frac{\Phi_0 z}{h} = \frac{\Phi_0 z}{h_0 + x\theta_y - y\theta_x} \tag{Eq. 12}$$

[0144] Here, J_e denotes the total current density in the electrolyte. Then, $J_e = J_0 + j_e$, where $J_0 = J_0(1+\beta\sin(w_b t))(-\hat{e}_z)$ is the unperturbed current density, and j_e is the perturbed current density in the electrolyte. Here, based on previously presented assumptions, j_e is purely vertical, and therefore, J_e must be purely vertical. Therefore, as shown in Eq. 13:

$$J_e = -\sigma\nabla\Phi(-\hat{e}_z) = -\sigma\frac{\partial\Phi}{\partial z}(-\hat{e}_z) = -\sigma\frac{\Phi_0}{h_0 + x\theta_y - y\theta_x}(-\hat{e}_z) \tag{Eq. 13}$$

[0145] When $\theta_x = 0 = \theta_y$, the system is at equilibrium, and there is no perturbed current. Hence, as shown in Eq. 14

$$J_e\,|_{\theta_x=0=\theta_y} = -\frac{\sigma\Phi_0}{h_0}(-\hat{e}_z) = J_0 = J_0(1 + \beta\sin(w_b t))(-\hat{e}_z) \tag{Eq. 14}$$

[0146] Using Eq. 14, Eq. 13 can be written as Eq. 15:

$$J_e = \frac{J_0(1 + \beta\sin(\omega_b t))h \cdot 0}{h_0 + x\theta_y - y\theta_x}(-\hat{e}_z) \tag{Eq. 15}$$

[0147] Using Eq. 14 and Eq. 15, the perturbed current density in the electrolyte can be described as shown in Eq. 16:

$$\begin{aligned} j_e &= J_e - J_0 \\ &= \left(-\frac{J_0(1 + \beta\sin(\omega_b t))h_0}{h_0 + x\theta_y - y^\theta x} + J_0(1 + \beta\sin(\omega_b t))\right)(\hat{e}_z) \\ &= J_0(1 + \beta\sin(\omega_b t))\left(\frac{x\theta_y - y\theta_x}{h_0 + x\theta_y - y\theta_x}\right)(\hat{e}_z) \end{aligned} \tag{Eq. 16}$$

[0148] If $\gamma = x\theta_y - y\theta_x$, then

$$j_e = \frac{\gamma}{h_o + \gamma}(\hat{e}_z).$$

Taylor expanding

$$\frac{\gamma}{h_o + \gamma}$$

around $\gamma = 0$ gives Eq. 17:

$$\frac{\gamma}{h_0 + \gamma} \approx 0 + \left.\frac{h_0 + \gamma - \gamma}{(h_0 + \gamma)^2}\right|_{\gamma=0}(\gamma - 0) + \ldots \approx \frac{\gamma}{h_0} \tag{Eq. 17}$$

[0149] Therefore, the perturbed current density in the electrolyte is (Eq. 18):

$$\begin{aligned} j_e &= J_0(1 + \beta\sin(\omega_b t))\frac{\gamma}{h_0 + \gamma}(\hat{e}_z) \\ &\approx \frac{J_0(1 + \beta\sin(\omega_b t))\gamma}{h_0}(\hat{e}_z) \\ &= \frac{J_0(\beta\sin(\omega_b t))(x\theta_y - y\theta_x)}{h_0}(\hat{e}_z) \end{aligned} \tag{Eq. 18}$$

3.4 Aluminum Plate's Moment of Inertia about x and y-Axis Through Pivot

[0150] In this example, and shown in FIGS. **7-8**, COM is assumed to be a center of mass, and $I_x = \int^M r^2 dM$; where r is a perpendicular distance from a point to the "x"-axis.

[0151] Moment of inertia about axis is parallel to the x-axis through COM of the plate (x' axis), as shown in FIGS. **7-8**. The x' axis is at z=−H/2 and y=0, resulting in the COM having coordinates (0, 0, −H/2). Considering that a point M has coordinates (x, y, z) at the aluminum plate, then the orthogonal project of M on the x' axis has coordinates (x, 0, −H/2).

$$r^2 = (x-x)^2 + (y-0)^2 + (z+\frac{H}{2})^2 = y^2 + (z+\frac{H}{2})^2 \quad \text{(Eq. 19)}$$

$$I_{x'_{COM}} = \int^M r^2 dm; \text{ where } dm = \quad \text{(Eq. 20)}$$

$$\rho_a dV = \rho_a L_x dzdy = \int_{-H/2}^{0}\int_{-L_{y/}/2}^{L_y/2} [y^2 + (z+\frac{H}{2})^2 \rho_a L_x dydz =$$

$$\rho_a L_x \int_{-H}^{0} [\frac{L_y^3}{12} + (z+\frac{H}{2})^2 L_y]dz =$$

$$\rho_a L_x \left[\frac{HL_y^3}{12} + \frac{H^3L_y}{3} - \frac{H^3L_y}{2} + \frac{H^3L_y}{4}\right] = \rho_a L_x H L_y [\frac{L_y^2}{12} + \frac{H^2}{12}]$$

$$\text{Similarly, } I_{y'_{COM}} = \rho_a L_x H L_y [\frac{L_x^2}{12} + \frac{H^2}{12}] \quad \text{(Eq. 21)}$$

3.5 Moment of Inertia about Axes Parallel to x' and y' Passing Through Pivot

[0152] Based on the model schematic shown in FIG. **9**:

$$I_{x''_{COM}} = I_{x'_{COM}} + md^2;\ m = \rho_a L_x H L_y \text{ and } d^2 = \left(h_0 + \frac{H}{2}\right)^2 \quad \text{(Eq. 22)}$$

[0153] where m is a mass of plate, and dis the distance between two axes.

[0154] Hence,

$$I_{x''} = \rho_a L_x H L_y \left[\frac{L_y^2}{12} + \frac{H^2}{12} + \left(h_0 + \frac{H}{2}\right)^2\right] \quad \text{(Eq. 23)}$$

Similarly,

$$I_{y''} = \rho_a L_x H L_y \left[\frac{L_x^2}{12} + \frac{H^2}{12} + \left(h_0 + \frac{H}{2}\right)^2\right]; \quad \text{(Eq. 24)}$$

[0155] where y" is parallel to y' passing through pivot.

3.6 Torques Due to Perturbed Lorentz Force

[0156] The horizontal components of the perturbed current within the aluminum plate interact with the unperturbed vertical magnetic field, $B_0=B_z(\hat{e}_z)$, giving rise to a perturbed Lorentz force:

$$f=j_{al}\times B_0 \quad \text{(Eq. 25)}$$

[0157] Where f is the Lorentz force per unit volume, Eq. 25 can be written as:

$$f^x=j_{al}^y B_0(\hat{e}_x) \quad \text{(Eq. 26)}$$

$$f^y=j_{al}^x B_0(-\hat{e}_y) \quad \text{(Eq. 27)}$$

[0158] If both sides of Eq. 26 are integrated along y and z directions, and Eq. 27 along z and x directions, then:

$$\int_{-L_y/2}^{L_y/2}\int_{-H}^{0} f^x dzdy = \int_{-L_y/2}^{L_y/2}\int_{-H}^{0} j_{al}^y B_0 dzdy(\hat{e}_x) \quad \text{(Eq. 28)}$$

$$\int_{-L_x/2}^{L_x/2}\int_{-H}^{0} f^y dzdx = \int_{-L_x/2}^{L_x/2}\int_{-H}^{0} j_{al}^x B_0 dzdx(-\hat{e}_y) \quad \text{(Eq. 29)}$$

[0159] The right-hand side of Eq. 28 and Eq. 29 are, respectively, the net flow of perturbed current along the x and y-directions inside of the aluminum plate. Hence, the distribution of the Lorentz force components along the x and y-directions are respectively:

$$F^x(y) = I_{al}^y(y)B_0(\hat{e}_x) = -\frac{J_0B_0(1+\beta\sin(\omega_b t))(\theta_x L_x)}{2h_0}\left[\left(\frac{L_y}{2}\right)^2 - y^2\right](\hat{e}_x) \quad \text{(Eq. 30)}$$

$$F^y(x) = -I_{al}^x(x)B_0(\hat{e}_y) = -\frac{J_0B_0(1+\beta\sin(\omega_b t))(\theta_y L_y)}{2h_0}\left[\left(\frac{L_x}{2}\right)^2 - x^2\right](\hat{e}_y) \quad \text{(Eq. 31)}$$

[0160] Using Eq. 30 and Eq. 31 and referring to FIGS. **6A-6B**, the distribution of the torque (arising from the Lorentz force) components, about the pivot, along the x and y-directions are, respectively, found to be:

$$\tau^x(x) = r_\perp^x F^y(x)(-\hat{e}_z\times\hat{e}_y) = \left(h_0 + \frac{H}{2}\right)F^y(x)(\hat{e}_x) \quad \text{(Eq. 32)}$$

$$\tau^y(y) = r_\perp^y F^x(y)(-\hat{e}_z\times\hat{e}_x) = \left(h_0 + \frac{H}{2}\right)F^x(y)(-\hat{e}_y) \quad \text{(Eq. 33)}$$

[0161] Finally, the net torques along the x and y-direction were respectively obtained by integrating Eq. 32 along the x-direction and Eq. 33 along the y-direction:

$$\tau_{Net}^x = \int_{-\frac{L_x}{2}}^{\frac{L_x}{2}} \tau^x(x)dx = -\left(h_0 + \frac{H}{2}\right)\frac{J_0B_0(1+\beta\sin(\omega_b t))(\theta_y L_y)}{h_0}\left(\frac{L_x}{12}\right)^3 \quad \text{(Eq. 34)}$$

$$\tau_{Net}^y = \int_{-\frac{L_y}{2}}^{\frac{L_y}{2}} \tau^y(y)dy = \left(h_0 + \frac{H}{2}\right)\frac{J_0B_0(1+\beta\sin(\omega_b t))(\theta_x L_x)}{h_0}\left(\frac{L_y}{12}\right)^3(\hat{e}_y) \quad \text{(Eq. 35)}$$

3.7 Equations of Motion

[0162] Conservation of angular momentum around horizontal axes parallel to x and y axes when the aluminum plate is at $\theta_x=0=\theta_y$, and passing through the pivot is used to describe the motion of the plate. As shown in FIGS. **6A-6B**, the only torques acting on the plate are the ones due to the Lorentz and gravity forces.

$$I_{xx}\alpha_x=\Sigma\tau=\tau_{Net}^x+\tau_{gravity}^x \quad \text{(Eq. 36)}$$

$$I_{yy}\alpha_y=\Sigma\tau=\tau_{Net}^y+\tau_{gravity}^y \quad \text{(Eq. 37)}$$

[0163] Where:

$$I_{xx} = \rho_a L_x H L_y \left[\frac{L_y^2}{12} + \frac{H^2}{12} + \left(h_0 + \frac{H}{2}\right)^2\right] \text{ and}$$

$$I_{yy} = \rho_a L_x H L_y \left[\frac{L_x^2}{12} + \frac{H^2}{12} + \left(h_0 + \frac{H}{2}\right)^2\right]$$

are the moments of inertia (as shown above), $\alpha_x=\ddot{\theta}_x\hat{e}_x$ and $\alpha_y=\ddot{\theta}_y\hat{e}_y$ are the angular acceleration along the x and y direction, respectively. While $\tau_{gravity}^x$ and $\tau_{gravity}^y$ are the torques due to the gravitational force along the x and y directions. Referring to FIGS. **6**A-**6**B:

$$\tau^{x}_{gravity} = r_{\perp} \times \mathrm{mg} = \rho_a L_x L_y H g\left(h_0 + \frac{H}{2}\right)\theta_x(-\hat{e}_x) \tag{Eq. 38}$$

$$\tau^{y}_{gravity} = r_{\perp} \times \mathrm{mg} = \rho_a L_x L_y H g\left(h_0 + \frac{H}{2}\right)\theta_y(-\hat{e}_y) \tag{Eq. 39}$$

[0164] The Eq. 38 and 39 can be rewritten as:

$$\ddot{\gamma}_x + \omega_x^2\gamma_x = -\frac{J_0B_0(1+\beta\sin(\omega_b t))}{\rho_{al}H}\gamma_y \tag{Eq. 40}$$

$$\ddot{\gamma}_y + \omega_y^2\gamma_y = \frac{J_0B_0(1+\beta\sin(\omega_b t))}{\rho_{al}H}\gamma_x \tag{Eq. 41}$$

[0165] where

$$\gamma_x = \frac{\theta_x}{L_x^2} \text{ and } \gamma_y = \frac{\theta_y}{L_y^2};$$

where θ_x, θ_y rotations about the x and y-axis, respectively.

[0166] In the cases where ϕ is not zero, the Eqs. 40 and 41 can also include a phase component:

$$\ddot{\gamma}_x + \omega_x^2\gamma_x = -\frac{J_0B_0(1+\beta\sin(\omega_b t + \phi))}{\rho_{al}H}\gamma_y \text{ and} \tag{Eq. 42}$$

$$\ddot{\gamma}_y + \omega_y^2\gamma_y = \frac{J_0B_0(1+\beta\sin(\omega_b t + \phi))}{\rho_{al}H}\gamma_x \tag{Eq. 43}$$

[0167] The double dot ($\ddot{\gamma}_x$) represents the second derivative with respect to time, specifically $\ddot{\gamma}_x$ represents an angular acceleration in the x-direction. The natural frequencies of the pure gravitational oscillations are denoted by:

$$\omega_x^2 \approx \frac{g\left(h_0 + \frac{H}{2}\right)}{L_y^2/12}, \text{ and} \tag{Eq. 44}$$

$$\omega_y^2 \approx \frac{g\left(h_0 + \frac{H}{2}\right)}{\frac{L_x^2}{12}}; \tag{Eq. 45}$$

where g is 9.81 m/s^2 is the acceleration due to gravity.

Example 4

4.1 Case Study I: Uniform Current Density, β=0

[0168] MATLAB, more specifically "ode45", was utilized to solve the system of coupled ODEs representing the Equations of motion of the pendulum (Eqs. 40 and 41). The extreme case where there is no sinusoidal component to the unperturbed current (β=0) was considered first.

[0169] It was shown (P. A. Davidson et al., Stability of interfacial waves in aluminium reduction cells. *Journal of Fluid Mechanics,* 362:273-295, 1998) that the onset of instability occurs when:

$$|\omega_x^2 - \omega_y^2| = \frac{2J_0B_0}{\rho_{al}H} = 2a \tag{Eq. 46}$$

[0170] The oscillations are stable as long as $|\omega_x^2 - \omega_y^2| > 2a$. For cell dimensions of h_0=4.5 cm, H=0.2 m, L_x=11 m and L_y=2.7 m, the natural frequencies are ω_x=1.5302 Hz and ω_y=0.3756 Hz. This implies that the stability threshold is at a=1.100206. It was shown that for the case of a DC current only, the oscillations in the model are unstable for values of "a" higher than the critical threshold. FIGS. **10**A-**10**D show numerical results for different values of a. It can be seen that the system becomes unstable at a=1.100207.

[0171] FIGS. **11**A-**11**C show additional exemplary data showing oscillations that can be present in the aluminum pot model with only DC applied. The natural frequencies of the model are ω_x=1.5302 Hz and w_y=0.3756 Hz. Initially, at t=0 seconds, a small wave is applied. As shown in FIG. **11**A, at the amplitude of the oscillations for 60 seconds and the stability parameter "a" slightly below the critical value, the oscillations are finite and growing in amplitude slowly. FIG. **11**B shows the same oscillations in panel a but for a substantially longer time. The oscillations are clearly finite, which indicates stability. As shown in FIG. **11**C, when the stability parameter "a" is increased slightly above the critical value, the oscillation amplitude increases by five orders of magnitude. Without wishing to be bound by any theory, this rapid growth of oscillations is associated with instability.

4.2 Case Study II: β≠0

[0172] With the numerical solver agreeing with theoretical results, attempting to stabilize the system by varying β and ω_b came next. First, a=1.1003 was set to ensure that the system is unstable, and ω_b=2π was fixed. β varied from 0.1 to 0.5 in steps of 0.05. A stable state was achieved at β≥0.3, as seen in FIGS. **12**A-**12**I.

[0173] FIGS. **13**A-**13**C show other exemplary oscillations of the aluminum pot model with the stability parameter a=1.1354. This value of a represents a 10% decrease in the cryolite thickness in the model having

$$\omega_b = \frac{\pi}{2} \text{ rad/s}, \phi = 0 \text{ rad}, \omega_x = 1.5302 \text{ Hz},$$

and ω_y=0.3756 Hz. Initially, at t=0 seconds, a small wave is applied. As shown in FIG. **13**A, β=0, which corresponds to DC current only. As shown, the oscillations are rapidly growing, indicating instability. In FIG. **13**B, β=0.23, meaning that an AC current is added with an amplitude of 23% of the DC current. At these β values, the oscillations are still appeared to be unstable. FIG. **13** C shows results for the case with β=0.24. It can be seen that at this β value, oscillations do not grow. This shows the aluminum pot is stabilized by adding an AC current with a suitable amplitude.

[0174] Next, β=0.1 and a=1.1003 were fixed creating an unstable scenario. In this experiment, ω_b was varied from 0 to 2π in steps of π/4. Unlike the case with varying β, the stability was not observed above a certain threshold. Instead, it was observed that the system stabilized at discrete values of ω_b. As shown in FIGS. **14**A-**14**I stability was achieved at ω=π/4, π/2, π, 5π/4.

[0175] FIGS. **15**A-**15**C show additional exemplary oscillations of the aluminum pot model with the stability parameter a=1.1354. This value of a represents a 10% decrease in the cryolite thickness in the model. The following system parameters have been assumed: β=0.23, ϕ=0 rad, ω_x=1.5302 Hz, and ω_y=0.3756 Hz. Initially, at t=0 seconds, a small wave is applied. FIG. **15**A show results for ω_b=0 rad/s, which corresponds to DC current only. As shown, the oscillations are rapidly growing, indicating instability. As shown in FIG. **15**B ω_b=0.3 rad/s, and the oscillations are still unstable. As shown in FIG. **15**C at ω_b=0.5 rad/s the oscillations' amplitude is not growing anymore. This shows again that aluminum pot can be stabilized by adding an AC current with a suitable angular frequency.

[0176] FIG. **16** depicts a schematic of the stability of the oscillations in the aluminum pot model for different combinations of β and ω_b. The stability parameter a=1.1354, which represents a 10% decrease in the cryolite thickness in the model. ϕ=0 rad, ω_x=1.5302 Hz, and ω_y=0.3756 Hz. As shown, for β=0 or ω_b=0 (which indicates a DC current only), the oscillations are always unstable when a is above its critical value (cryolite thickness is below its critical values). For some combinations of β and ω_b the oscillations can be successfully stabilized.

Example 5

[0177] In this example, the shape of the interface was simulated using an MHD-VALDIS, a software package written specifically for simulating aluminum reduction cells and used widely throughout the industry. The instantaneous and time-averaged interface shapes are shown in FIG. **17**, along with the difference between the two, as referred herein as a deviation. This deviation was used to quantify the interface deformation.

[0178] Without wishing to be bound by any theory, it was assumed that the resonant instability can occur when two gravity-wave modes on the aluminum-salt interface couple to each other, producing a wave that circulates counter-clockwise and is amplified by the electrical current. FIG. **18**A shows the evolution of the interface deformation, illustrating a circulating motion. In this simulation, an anode-cathode distance (ACD, the thickness of the salt layer) was assumed to be 4.0 cm, and a value of a direct current was assumed to be 180 kA. As shown in FIG. **18**E, under such simulated conditions, the resonant instability has occurred, and the root-mean-square deformation increased dramatically. This behavior was consistent with an exponential increase over time, and the best-fit exponential curve had a growth rate of 0.002915 Hz, corresponding to a doubling time of 321 s. An aluminum reduction cell is not expected to be operable under these conditions.

[0179] At any moment, the shape of the interface deviation can be written as a sum of gravity wave modes, as shown in Eq. 47:

$$z(x, y, y) = \sum_{n,m=0}^{\infty} C_{nm}(t)\cos\frac{n\pi}{L_x}x\cos\frac{m\pi}{Ly}y \tag{47}$$

[0180] where z is the deviation of the interface from its average shape; (x; y) are Cartesian coordinates in the horizontal plane; t is time; (n;m) are positive integers; the spectral power C_{nm}(t), which varies over time, is the magnitude of the mode specified by (n;m); and (L_x; L_y) are the lengths of the cell in the (x; y) directions, respectively. FIG. **18**F shows that the strongest modes in this simulation are (n;m)=(2; 0) and (0; 2). FIG. **18**G shows the time evolution of their strengths. As both grow, they oscillate 180° out of phase (one is strong while the other is weak), the hallmark of a circulating wave.

[0181] In aspects where no current is present, the frequency of any wave mode (n, m) can be calculated according to Eq. 48:

$$f_{nm} = \frac{1}{2\pi}\sqrt{\frac{\rho_1-\rho_2}{\frac{\rho_1}{h_1}+\frac{\rho_2}{h_2}}g\left(\frac{n^2\pi^2}{L_x^2}+\frac{m^2\pi^2}{L_y^2}\right)} \tag{48}$$

[0182] Where (ρ_1, ρ_2) are the densities of the aluminum and salt, respectively; (h_1; h_2) are the thicknesses of the aluminum and salt, respectively; and g is the gravitational acceleration. This expression can be used to accurately approximate the frequencies of wave modes in simulation, even though a large current is present, as shown in FIG. **18**H. The plot shows the power spectrum of oscillation of a single point on the interface. Its motion is dominated by a frequency that closely matches the theoretical frequency of the (2; 0) mode and is almost exactly half the theoretical frequency of the (0; 2) mode, characteristic of a resonance.

[0183] Without wishing to be bound by any theory, it is hypothesized that the resonant instability occurs only when two or more adjacent gravity-wave modes couple to produce a counter-clockwise circulation. The methods disclosed herein prevent such a formation and growth of such waves by adding an oscillating component to the electrical current running through the cell. It is understood that any frequencies and amplitudes as disclosed herein can be chosen for the oscillating current component.

[0184] In certain aspects, the frequencies are chosen for an oscillating component such that a standing wave is formed instead of circulation. FIGS. **19**A-D show the evolution of the interface deformation in a simulation with the same conditions as above (4.0 cm ACD and 180 kA steady current) but with an addition of a 19.8 kA oscillating component with a frequency of 0.045 Hz. It was found that the interface shape in such aspect evolves not according to circulation but according to a standing wave. In such aspects, methods disclosed herein prevent the interface deformation from growing large over time, as shown in FIG. **19**E. It is further understood that under such conditions, an aluminum reduction cell can operate successfully.

[0185] FIG. **19**F shows that the strongest modes in this simulation is (n;m)=(0; 2). The (2; 0) mode is present but is much weaker than in the simulation without an oscillating current component. FIG. **19**G shows the time evolution of mode strengths. Instead of growing stronger and stronger over time, the modes oscillate steadily. The (2; 0) mode was found to remain weak throughout the simulation. FIG. **19**H shows the power spectrum of oscillation of a single point on the interface. Its motion is dominated by two frequencies, one closely matching the theoretical frequency of the (0; 2) mode and the other closely matching the theoretical frequencies of the (2; 0) and (0; 1) modes. The ratio of the two frequencies is almost exactly two, characteristic of a resonance.

[0186] Altogether, these results show that adding an oscillating current component with frequency, for example, and without limitation of 0.045 Hz, can drive an (n;m)=(0; 2) mode whose frequency is nearly the same as the 0.0498 Hz predicted by theory. The (0; 2) mode can also prevent the formation and growth of the (2; 0) and (0; 1) modes that would result in a circulating wave and give rise to a resonant instability, making the aluminum cell inoperable. Instead, standing waveforms and the cell can be operated indefinitely.

[0187] Other simulations were performed using a smaller value of ACD. In one exemplary simulation, an ACD of 3.8 cm and 180 kA steady current with a 19.8 kA oscillation at 0.045 Hz were used. The (0; 2) mode was again excited, and the cell was again stable, allowing indefinite operation.

[0188] This cell is known to be stable without an oscillating component if the ACD is at least 4.2 cm. The methods disclosed herein allow, for example, a 9.5% reduction in ACD, which would cause a similar reduction in energy consumption and substantial cost savings.

[0189] In an additional exemplary simulation, an ACD of 4.0 cm and 180 kA steady current with a 19.8 kA oscillation at 0.069 Hz were also tested. That frequency excited the (6; 0) mode, whose frequency is predicted to be 0.0688 Hz. The (6; 0) mode was found to couple with the (0; 2) mode to produce a standing wave, preventing the (0; 1) and (2; 0) modes from coupling to produce circulation and the resulting resonant instability.

[0190] In an additional exemplary simulation, an ACD of 3.6 cm and 180 kA steady current with a 19.8 kA oscillation at 0.069 Hz, finding that the cell was nearly stable even when the salt layer thickness was reduced 14% from its stable value (4.2 cm).

[0191] In an additional exemplary simulation, an ACD of 4.0 cm and 180 kA steady current with a 19.8 kA oscillation at 0.0227 Hz was used. That frequency drove the (2; 0) mode, whose frequency is predicted to be 0.0229 Hz. Driving even that mode frustrated its ability to couple to the (0; 1) mode and produce a circulation; the cell was nearly stable.

[0192] The claims are not intended to include, and should not be interpreted to include, means-plus- or step-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase(s) "means for" or "step for," respectively.

[0193] In view of the described processes and compositions, hereinbelow are described certain more particularly described aspects of the inventions. These particularly recited aspects should not, however, be interpreted to have any limiting effect on any different claims containing different or more general teachings described herein, or that the "particular" aspects are somehow limited in some way other than the inherent meanings of the language and formulas literally used therein.

Aspects:

[0194] Aspect 1: A system comprising: a) an electrolytic cell comprising: i) an anode; ii) a cathode; and iii) a molten electrolyte having a predetermined thickness; b) a direct current source that is in electrical communication with the electrolytic cell and is configured to provide a direct current (DC) having a predetermined amplitude and to initiate an electrolysis reaction in the electrolytic cell; c) a device comprising an alternating current source; wherein the device is in electrical communication with the electrolytic cell and is configured to provide an alternating current (AC) to the electrolytic cell, wherein the AC comprises an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase; and wherein the device is in feedback loop communication with the electrolytic cell; and wherein the electrolytic cell exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell.

[0195] Aspect 2: The system of Aspect 1, wherein the AC is further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, wherein the β is from greater than 0 to about 1.

[0196] Aspect 3: The system of Aspect 1 or 2, wherein the predetermined frequency of the AC is from greater than 0 to about 120π rad/s.

[0197] Aspect 4: The system of any one of Aspects 1-3, wherein the electrolytic cell is an aluminum electrolysis cell.

[0198] Aspect 5: The system of any one of Aspects 1-4, wherein the molten electrolyte comprises cryolite.

[0199] Aspect 6: The system of any one of Aspects 1-5, wherein the anode and/or cathode comprises carbon.

[0200] Aspect 7: The system of any one of Aspects 1-6, wherein the predetermined thickness of the molten electrolyte is equal to or less than about 4.5 cm.

[0201] Aspect 8: The system of any one of Aspects 1-7, wherein the direct current source is present in the device.

[0202] Aspect 9: The system of any one of Aspects 1-8, wherein the system further comprises a unit configured to measure oscillations of the molten salt electrolyte as a function of the DC and AC applied to the electrolytic cell; and wherein the unit is in feedback loop communication with the device and the electrolytic cell.

[0203] Aspect 10: The system of any one of Aspects 1-9, wherein the oscillatory current waveform of AC comprises a sinusoidal, cosinusoidal, triangular, or square shape.

[0204] Aspect 11: The system of any one of Aspects 1-10, wherein the predetermined amplitude, frequency, and/or phase of the AC is configured to be adjusted in response to the feedback communication from the electrolytic cell.

[0205] Aspect 12: A method comprising: a) providing an electrolytic cell comprising: i) an anode; ii) a cathode; and iii) a molten electrolyte having a predetermined thickness; b) applying a direct current (DC) having a predetermined amplitude to the electrolytic cell to initiate an electrolysis reaction; c) applying an alternating current (AC) comprising an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase to the electrolytic cell, and d) measuring oscillations in the molten salt electrolyte as a function of the DC and AC applied to the electrolytic cell.

[0206] Aspect 13: The method of Aspect 12, wherein the electrolytic cell exhibits substantially no change in the oscillations present in the molten salt electrolyte over a predetermined period of time.

[0207] Aspect 14: The method of Aspect 12 or 13, wherein the AC is provided by a device comprising an alternating current source that is in electrical communication with the electrolytic cell.

[0208] Aspect 15: The method of Aspect 14, wherein the DC is provided by the device further comprising a direct current source.

[0209] Aspect 16: The method of any one of Aspects 12-14, wherein the DC is provided by a separate direct current source.

[0210] Aspect 17: The method of any one of Aspects 12-16, wherein the measuring is performed with a unit that is in feedback loop communication with the device and the electrolytic cell.

[0211] Aspect 18: The method of any one of Aspects 14-17, wherein the device is in feedback loop communication with the electrolytic cell.

[0212] Aspect 19: The method of any one of Aspects 12-18, wherein the oscillatory current waveform comprises a sinusoidal, cosinusoidal, triangular, or square shape.

[0213] Aspect 20: The method of any one of Aspects 12-19, wherein the AC is further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, and wherein the β is from greater than 0 to about 1.

[0214] Aspect 21: The method of any one of Aspects 12-20, wherein the predetermined frequency of the AC is from greater than 0 to about 120π rad/s.

[0215] Aspect 22: The method of any one of Aspects 20-21, further comprising a step of adjusting the predetermined amplitude, frequency, and/or phase, or β of AC based on the feedback communication from the electrolytic cell.

[0216] Aspect 23: The method of any one of Aspects 12-22, wherein the electrolytic cell is an aluminum electrolysis cell.

[0217] Aspect 24: The method of any one of Aspects 12-23, wherein the molten electrolyte comprises cryolite.

[0218] Aspect 25: The method of any one of Aspects 12-24, wherein the anode and/or cathode comprises carbon.

[0219] Aspect 26: The method of any one of Aspects 12-25, wherein the predetermined thickness of the molten electrolyte is equal to or less than about 4.5 cm.

[0220] Aspect 27: A method comprising: applying an alternating current (AC) comprising an oscillatory current waveform to an electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis.

[0221] Aspect 28: The method of Aspect 27, wherein the electrolyte is a molten salt electrolyte.

[0222] Aspect 29: The method of Aspect 27 or 28, wherein a direct current (DC) is applied to the electrolytic cell for a second predetermined time prior to applying the AC.

[0223] Aspect 30: The method of Aspect 29, wherein the direct current is continued to be applied for the first predetermined time simultaneously with applying the AC.

[0224] Aspect 31: The method of Aspect 27 or 28, wherein a direct current (DC) is applied to the electrolytic cell simultaneously with applying the AC for the first predetermined time.

[0225] Aspect 32: The method of Aspect 29-30, wherein the second predetermined time is defined by a time period measured from applying the DC to an appearance of a resonant instability in the electrolytic cell.

[0226] Aspect 33: The method of any one of Aspects 27-32, wherein the electrolytic cell further comprises an anode and a cathode.

[0227] Aspect 34: The method of Aspect 33, wherein the amplitude, frequency and/or phase are predetermined such that an anode-to-cathode distance is reduced when it is compared to an anode-to-cathode distance of a substantially identical reference electrolytic cell in the absence of applying an AC.

[0228] Aspect 35: The method of any one of Aspects 27-34, wherein the electrolytic cell exhibits an increase in the energy efficiency when is compared to the energy efficiency of a substantially identical reference electrolytic cell in the absence of applying the AC.

[0229] Aspect 36: The method of any one of Aspects 34-35, wherein the electrolytic cell exhibits an increase in the energy efficiency that is substantially proportional to a reduction in the anode-to-cathode distance.

[0230] Aspect 37: The method of any one of Aspects 34-36, wherein the electrolytic cell exhibits an increase in the energy efficiency of at least about 5% when compared to the substantially identical reference electrolytic cell in the absence of applying an AC.

[0231] Aspect 38: The method of any one of Aspects 27-37, wherein the waveform is defined by a plurality of modes that together form a standing wave.

[0232] Aspect 39: The method of Aspect 38, wherein the plurality of modes of the waveform are configured to disrupt a formation and/or growth of circulating waves.

[0233] Aspect 40: The method of any one of Aspects 27-39, wherein the AC is provided by a device comprising an alternating current source that is in electrical communication with the electrolytic cell.

[0234] Aspect 41: The method of any one of Aspects 29-40, wherein the DC is provided by the device further comprising a direct current source.

[0235] Aspect 42: The method of any one of Aspects 29-41, wherein the DC is provided by a separate direct current source.

[0236] Aspect 43: The method of any one of Aspects 29-42, further comprising measuring the current oscillations.

[0237] Aspect 44: The method of Aspect 43, wherein the measuring is performed by a controlling unit that is in a feedback loop communication with the device and the electrolytic cell such that it is configured to receive an input communication comprising a first data from the device and/or the electrolytic cell and provide an output communication to the device and/or the electrolytic cell, wherein the output communication comprises a second data adjusted for the first data.

[0238] Aspect 45: The method of any one of Aspects 43-44, wherein the device is in a feedback loop communication with the electrolytic cell.

[0239] Aspect 46: The method of any one of Aspects 27-45, wherein the oscillatory current waveform comprises a sinusoidal, cosinusoidal, triangular, or square shape.

[0240] Aspect 47: The method of any one of Aspects 29-46, wherein the AC is further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, and wherein the β is from greater than 0 to about 0.15.

[0241] Aspect 48: The method of any one of Aspects 27-47, wherein the frequency of the AC is from about 0.01 Hz to about 0.5 Hz (about π/50 rad/s to about n rad/s).

[0242] Aspect 49: The method of any one of Aspects 44-48, further comprising a step of adjusting the predetermined amplitude, frequency, and/or phase, or β of AC based on the feedback communication from the electrolytic cell.

[0243] Aspect 50: The method of any one of Aspects 27-49, wherein the electrolytic cell is an aluminum electrolysis cell.

[0244] Aspect 51: The method of any one of Aspects 28-50, wherein the molten electrolyte comprises cryolite.

[0245] Aspect 52: The method of any one of Aspects 33-51, wherein the anode and/or cathode comprises carbon.

[0246] Aspect 53: The method of any one of Aspects 27-52, wherein the electrolyte comprises a thickness equal to or less than about 4.5 cm.

[0247] Aspect 54: The method of any one of Aspects 27-53, wherein the thickness of the electrolyte is between about 3 cm to about 4.3 cm.

[0248] Aspect 55: A method comprising: a) providing a first data to a computational processor, wherein the first data comprises at least one of one or more of geometric parameters of an electrolytic cell, a cathode-to-anode-distance of the electrolytic cell, a value of a direct current; an amplitude of a direct current, a thickness of a metal layer, material properties of a metal, material properties of an electrolyte, material properties of a cathode, material properties of an anode, or any combination thereof; b) analyzing the first data by the computational processor to provide a second data comprising parameters of an alternating current (AC) wherein the parameters comprise one or more of a first amplitude, a first frequency, and/or a first phase of an oscillatory current form of the AC; and c) applying the AC having one or more parameters present in the second data to the electrolytic cell to stabilize the electrolytic cell.

[0249] Aspect 56: The method of Aspect 55, further comprising: d) collecting a third data from the electrolytic cell and transferring the third data to the computational processor to analyze the performance of the electrolytic cell; e) analyzing the third data by the computational processor to provide a fourth data comprising parameters of the alternating current (AC) wherein the parameters comprise one or more of a second amplitude, a second frequency, and/or a second phase of an oscillatory current form of the AC; and f) applying the AC having one or more parameters present in the fourth data to the electrolytic cell.

[0250] Aspect 57: The method of Aspect 56, comprising repeating steps of d)-f) until the electrolytic cell is stabilized such that substantially no change in a current oscillation is observed in an electrolyte during electrolysis.

[0251] Aspect 58: A method for increasing energy efficiency in an electrolytic cell comprising: applying an alternating current (AC) comprising an oscillatory current waveform to the electrolytic cell comprising an electrolyte for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis; and wherein the energy efficiency is increased by at least about 5% when compared to a substantially identical reference electrolytic cell in the absence of applying an AC.

[0252] Aspect 59: A system comprising: a) an electrolytic cell comprising: i) an anode; iii) a cathode; and iii) an electrolyte having a predetermined thickness; b) a direct current source that is in electrical communication with the electrolytic cell and is configured to provide a direct current (DC) having a predetermined amplitude and to initiate an electrolysis reaction in the electrolytic cell; c) a device comprising an alternating current source (AC); wherein the device is in electrical communication with the electrolytic cell and is configured to provide an alternating current (AC) to the electrolytic cell, wherein the AC comprises an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase; and wherein the device is in feedback loop communication with the electrolytic cell; and wherein the electrolytic cell exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell.

[0253] Aspect 60: The system of Aspect 59, wherein the AC is further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, wherein the β is from greater than 0 to about 0.15.

[0254] Aspect 61: The system of Aspect 59 or 60, wherein the predetermined frequency of the AC is from about 0.01 Hz to about 0.5 Hz (about $\pi/50$ rad/s to about π rad/s).

[0255] Aspect 62: The system of any one of Aspects 59-61, wherein the electrolytic cell is an aluminum electrolysis cell.

[0256] Aspect 63: The system of any one of Aspects 59-62, wherein the electrolyte is a molten electrolyte.

[0257] Aspect 64: The system of Aspect 63, wherein the molten electrolyte comprises cryolite.

[0258] Aspect 65: The system of any one of Aspects 59-64, wherein the anode and/or cathode comprises carbon.

[0259] Aspect 66: The system of any one of Aspects 59-65, wherein the predetermined thickness of the electrolyte is equal to or less than about 4.5 cm.

[0260] Aspect 67: The system of any one of Aspects 59-66, wherein the thickness of the electrolyte is between about 3 cm to about 4.3 cm.

[0261] Aspect 68: The system of any one of Aspects 59-67, wherein the amplitude, frequency and/or phase are predetermined such that an anode-to-cathode distance is reduced when it is compared to an anode-to-cathode distance of a substantially identical reference electrolytic cell in the absence of providing the AC.

[0262] Aspect 69: The system of any one of Aspects 59-68, wherein the electrolytic cell exhibits an increase in the energy efficiency when is compared to the energy efficiency of a substantially identical reference electrolytic cell in the absence of providing the AC.

[0263] Aspect 70: The system of any one of Aspects 59-69, wherein the electrolytic cell exhibits an increase in the energy efficiency that is substantially proportional to a reduction in the anode-to-cathode distance.

[0264] Aspect 71: The system of any one of Aspects 59-70, wherein the electrolytic cell exhibits an increase in the energy efficiency of at least about 5% when is compared to the substantially identical reference electrolytic cell in the absence of providing the AC.

[0265] Aspect 72: The system of any one of Aspects 61-71, wherein the waveform is defined by a plurality of modes that together form a standing wave.

[0266] Aspect 73: The system of Aspect 72, wherein the plurality of modes of the waveform are configured to disrupt a formation and/or growth of circulating waves.

[0267] Aspect 74: The system of any one of Aspects 59-73, wherein the direct current source is present in the device.

[0268] Aspect 75: The system of any one of Aspects 59-74, wherein the system further comprises a controlling unit configured to measure oscillations of the molten salt electrolyte as a function of the DC and AC applied to the electrolytic cell; and wherein the controlling unit is in a feedback loop communication with the device and the electrolytic cell.

[0269] Aspect 76: The system of any one of Aspects 59-75, wherein the oscillatory current waveform of AC comprises a sinusoidal, cosinusoidal, triangular, or square shape.

[0270] Aspect 77: The system of Aspect 59-76, wherein the predetermined amplitude, frequency, and/or phase of the AC is configured to be adjusted in response to the feedback communication from the electrolytic cell.

1. A method comprising:

applying an alternating current (AC) comprising an oscillatory current waveform to an electrolytic cell comprising an electrolyte, an anode, and a cathode for a first predetermined time, wherein waveform comprises an amplitude, frequency and/or phase that are predetermined to stabilize the electrolytic cell such that substantially no change in a current oscillation is observed in the electrolyte during electrolysis.

2. (canceled)

3. The method of claim **1**, wherein a direct current (DC) is applied to the electrolytic cell for a second predetermined time prior to applying the AC, wherein the second predetermined time is defined by a time period measured from applying the DC to an appearance of a resonant instability in the electrolytic cell.

4. The method of claim **3**, wherein the direct current is continued to be applied for the first predetermined time simultaneously with applying the AC.

5. The method of claim **1**, wherein a direct current (DC) is applied to the electrolytic cell simultaneously with applying the AC for the first predetermined time.

6. (canceled)

7. (canceled)

8. The method of claim **1**, wherein the amplitude, frequency and/or phase are predetermined such that an anode-to-cathode distance is reduced when it is compared to an anode-to-cathode distance of a substantially identical reference electrolytic cell in the absence of applying an AC, and wherein the electrolytic cell exhibits an increase in the energy efficiency that is substantially proportional to a reduction in the anode-to-cathode distance.

9. (canceled)

10. (canceled)

11. (canceled)

12. The method of claim **1**, wherein the waveform is defined by a plurality of modes that together form a standing wave, and wherein the plurality of modes of the waveform are configured to disrupt formation and/or growth of circulating waves.

13. (canceled)

14. The method of claim **1**, wherein the AC is provided by a device comprising an alternating current source that is in electrical communication with the electrolytic cell.

15. The method of claim **14**, wherein, the device further comprises a direct current source configured to provide the DC or wherein the DC is provided by a separate direct current source.

16. (canceled)

17. The method of claim **1**, further comprising measuring the current oscillations, wherein the measuring the current oscillations is performed by a controlling unit that is in a feedback loop communication with the device and the electrolytic cell such that it is configured to receive an input communication comprising a first data from the device and/or the electrolytic cell and provide an output communication to the device and/or the electrolytic cell, wherein the output communication comprises a second data adjusted for the first data.

18. (canceled)

19. (canceled)

20. (canceled)

21. The method of claim **3**, wherein the AC is further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, and wherein the β is from greater than 0 to about 0.15, and/or wherein the frequency of the AC is from about 0.01 Hz to about 0.5 Hz (about $\pi/50$ rad/s to about π rad/s).

22. (canceled)

23. The method of claim **17**, further comprising a step of adjusting the predetermined amplitude, frequency, and/or phase, or β of AC based on the feedback communication from the electrolytic cell.

24. The method of claim **1**, wherein the electrolytic cell is an aluminum electrolysis cell and wherein the electrolyte is a molten salt electrolyte.

25. (canceled)

26. (canceled)

27. The method of claim **1**, wherein the electrolyte comprises a thickness equal to or less than about 4.5 cm.

28. (canceled)

29. A method comprising:

a) providing a first data to a computational processor, wherein the first data comprises at least one of one or more of geometric parameters of an electrolytic cell, a cathode-to-anode-distance of the electrolytic cell, a value of a direct current; an amplitude of a direct current, a thickness of a metal layer, material properties of a metal, material properties of an electrolyte, material properties of a cathode, material properties of an anode, or any combination thereof;

b) analyzing the first data by the computational processor to provide a second data comprising parameters of an alternating current (AC) wherein the parameters comprise one or more of a first amplitude, a first frequency, and/or a first phase of an oscillatory current form of the AC;

c) applying the AC having one or more parameters present in the second data to the electrolytic cell to stabilize the electrolytic cell.

30. The method of claim **29**, further comprising:

d) collecting a third data from the electrolytic cell and transferring the third data to the computational processor to analyze the performance of the electrolytic cell;

e) analyzing the third data by the computational processor to provide a fourth data comprising parameters of the alternating current (AC) wherein the parameters comprise one or more of a second amplitude, a second frequency, and/or a second phase of an oscillatory current form of the AC; and

f) applying the AC having one or more parameters present in the fourth data to the electrolytic cell; and optionally comprising repeating steps of d)-f) until the electrolytic cell is stabilized such that substantially no change in a current oscillation is observed in an electrolyte during electrolysis.

31. (canceled)

32. (canceled)

33. A system comprising:

a) an electrolytic cell comprising:
  i) an anode;
  ii) a cathode; and
  iii) a molten salt electrolyte having a predetermined thickness;
b) a direct current source that is in electrical communication with the electrolytic cell and is configured to provide a direct current (DC) having a predetermined amplitude and to initiate an electrolysis reaction in the electrolytic cell;
c) a device comprising an alternating current source (AC); wherein the device is in electrical communication with the electrolytic cell and is configured to provide an alternating current (AC) to the electrolytic cell, wherein the AC comprises an oscillatory current waveform defined by a predetermined amplitude, frequency, and/or phase; and wherein the device is in feedback loop communication with the electrolytic cell;
  wherein the AC is further defined by a non-dimensional amplitude ratio β of the predetermined amplitude of the AC to the predetermined amplitude of the DC, wherein the β is from greater than 0 to about 0.15;
  wherein the predetermined frequency of the AC is from about 0.01 Hz to about 0.5 Hz (about π/50 rad/s to about π rad/s); and
wherein the electrolytic cell exhibits substantially no change in oscillations present in the molten salt electrolyte over a predetermined period of time when the AC is provided to the electrolytic cell.

34. (canceled)

35. (canceled)

36. The system of claim **33**, wherein the electrolytic cell is an aluminum electrolysis cell.

37. (canceled)

38. (canceled)

39. (canceled)

40. The system of claim **33**, wherein the predetermined thickness of the electrolyte is equal to or less than about 4.5 cm.

41. (canceled)

42. The system of claim **33**, wherein the amplitude, frequency and/or phase are predetermined such that an anode-to-cathode distance is reduced when it is compared to an anode-to-cathode distance of a substantially identical reference electrolytic cell in the absence of providing the AC, and wherein the electrolytic cell exhibits an increase in the energy efficiency that is substantially proportional to a reduction in the anode-to-cathode distance.

43. (canceled)

44. (canceled)

45. (canceled)

46. (canceled)

47. (canceled)

48. (canceled)

49. The system of claim **33**, wherein the system further comprises a controlling unit configured to measure oscillations of the molten salt electrolyte as a function of the DC and AC applied to the electrolytic cell; and wherein the controlling unit is in a feedback loop communication with the device and the electrolytic cell.

50. (canceled)

51. (canceled)

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