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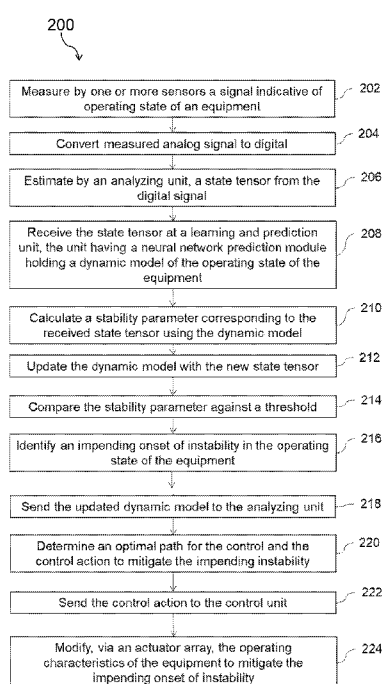


FIG. 2A

(57) Abstract: Disclosed are devices and methods of detecting and mitigating oscillatory instabilities in systems with turbulent flow, such as thermoacoustic, aeroacoustic or aeroelastic equipment. The system includes a sensor array 112 for measuring one or more parameters of an operating equipment S, and an analysis and prediction unit 104. The analysis and prediction unit is configured to estimate a state tensor to identify a state of the equipment indicating stable operation or impending oscillatory instability. The system further includes an actuator array 112 configured to implement a control action to promote stable operation of the equipment S. Methods for robust prediction of the state of stability are also disclosed. A neural ordinary differential equation (ODE) method of predicting stability or instability is disclosed, involving forming a neural network that incorporates an equation characteristic of the operational state. The invention further discloses a hybrid convolutional neural network based prediction method for stability.

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**DEVICE AND METHOD TO PREDICT THE ONSET OF OSCILLATORY
INSTABILITIES IN SYSTEMS WITH TURBULENT FLOW**

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 63/052867 entitled A DEVICE AND METHOD TO PREDICT THE ONSET OF OSCILLATORY INSTABILITIES IN SYSTEMS WITH TURBULENT FLOW filed on July 16, 2020.

FIELD OF THE INVENTION

[0002] The present invention is generally related to devices and methods for turbulent flow systems and in particular to devices and methods of predicting behavior thereof.

BACKGROUND AND DESCRIPTION OF RELATED ART

[0003] Systems that involve fluid flow often exhibit, high amplitude periodic oscillations resulting from undesirable positive feedback between oscillations in multiple subsystems. Examples include: thermoacoustic instability, aeroelastic instability, and aeroacoustic instability. In systems with confined combustion, thermoacoustic instability is caused by the feedback between the unsteady heat release rate and the acoustic field of the confinement. Oscillations in structures immersed in an unsteady flow can be coupled with the fluctuations in the flow resulting in a positive feedback that cause large amplitude limit cycle oscillations known as, aeroelastic instability. Oscillatory flow structures (such as vortices, shear layers) when in positive feedback with the acoustic field of a system, can cause aeroacoustic instability. Such oscillatory instabilities cause increased wear and tear, and even damage to the corresponding system.

[0004] Oscillatory instabilities are also common in structural elements suspended in fluid flows. Commonly known as aeroelastic instabilities, these instabilities are the result

of a positive coupling among the elastic, inertial, and aerodynamic forces. These undesired and potentially catastrophic sustained oscillations of the structure are also known as aeroelastic flutter. Such instabilities affect elastic bodies such as airplanes, wind turbines, skyscrapers, and suspension bridges. Although the dynamics of these have been studied over a long time, prognosis and mitigation of these oscillations remain a serious challenge.

SUMMARY OF THE INVENTION

[0005] The present invention in its various embodiments discloses systems, devices and methods for predicting and mitigating oscillatory instabilities in turbulent flow equipment. In one embodiment, a system for predicting and controlling onset of oscillatory instability in a turbulent flow equipment, is disclosed. The system comprises a sensor array comprising at least one sensor of a piezoelectric pressure transducer, a microphone or a strain gauge to measure analog signals, an analog to digital converter for converting the analog signals to a digital signal an analyzing unit, and a learning and prediction unit. The analyzing unit may be configured to estimate a state tensor including multidimensional data from the digital signal, or to implement a control action to promote stable operation of the equipment. The learning and prediction unit may be configured for classifying and recognizing patterns present in multidimensional data to identify potential onset of an unstable operating state of the equipment.

[0006] In various embodiments, the system may further comprise an actuator array present on the equipment, the actuator array configured to implement the control action to promote a stable operating state of the equipment. In various embodiments, the equipment may be a thermoacoustic equipment, an aeroacoustic equipment or an aeroelastic equipment.

[0007] In some embodiments, the equipment may be a thermoacoustic or an aeroacoustic equipment, and the actuator array comprises one or more of cooling holes,

staged fuel injectors, micro swirlers, water injectors, or dampers. In some embodiments, the equipment is an aeroelastic equipment, and the actuator array comprises counterweights, fins, microthrusters, flywheels or gyros.

[0008] In some embodiments, the invention discloses a method of predicting and mitigating occurrence of a potentially unstable operating state of an equipment. The method comprises measuring, by one or more sensors in a sensor array, a signal indicative of operating state of the equipment to obtain a measured signal, converting, by analog to digital converter the measured signal into a digital signal, estimating, by an analyzing unit, a state tensor from the digital signal, receiving the state tensor at a learning and prediction unit, the unit having a neural network prediction module with a dynamic model of the operating state of the equipment, calculating a stability parameter corresponding to the received state tensor using the dynamic model, updating the dynamic model with the state tensor, comparing the stability parameter against a threshold; and identifying an impending onset of instability in the operating state of the equipment.

[0009] In some embodiments, the method may further comprise sending the updated dynamic model to the analyzing unit, determining, by the analyzing unit an optimal path for control and control action to mitigate the impending stability, sending the control action to a control unit; and modifying, by the control unit via an actuator array, the operating state of the equipment to mitigate the impending instability.

[0010] In some embodiments, the neural network method is one of a neural ordinary differential equation (ODE) method, or a hybrid convolutional neural network method.

[0011] In various embodiments, the neural network is an ODE neural network and the method comprises in step a), constructing a neural network (NN) with at least 3 layers, that maps state variables $p(t)$ of an operational state to a dynamic state variable $z(t)$ and to its time derivative $\dot{z}$, wherein $\dot{z} = f(z, t, w)$. The next step b) involves defining the NN with nodes in each layer and specifying a corresponding activation function. Then in c)

weighted inputs corresponding to time series data at times t are received. In the next step d), the sum of the weighted inputs at each node for initial time t_0 , to a final time instance t_1 for the corresponding operational states to obtain a weight matrix are computed. In the next step e), the method involves computing a distance in the weight matrix defined as $d^{(i)} = |\bar{w}^{(i)} - w^{(r)}|$, wherein $\bar{w}^{(i)}$ is an averaged weight over a window of n_w samples, $w^{(r)}$ is an average weight corresponding to an unstable state. In a final step f), a sum of the distances is computed and a parameter μ_1 is obtained that varies inversely as the sum, to obtain a measure of stability of the operational state.

[0012] In some embodiments, in step d) the final state predicted by neural ODE, $z_p(t_1)$ is given by:

$$z_p(t_1) = \int_{t_0}^{t_1} f(z(t), t, w) dt, \text{ wherein,}$$

an error in the prediction is given by:

$$J = \left(z(t_1) - z_p(t_1) \right)^2.$$

In some embodiments, the method comprises, prior to step d), training the neural network using weights learned from a first sample data $w^{(1)}$ as initial guess to find weights for subsequent samples. Then the neural network is trained on the i^{th} sample data to get corresponding weights of NN as $w^{(i)}$. Then, the weights are averaged over a window of n_w samples, given by

$$\bar{w}^{(i)} = \frac{1}{n_w} \sum_{j=(i-n_w+1)}^{j=i} w^{(j)}$$

[0013] In some embodiments, the neural network is a hybrid convolutional neural network (CNN). The method comprises providing an input adjacency matrix of nodes to construct the convolutional neural network and providing two or more convolutional layers in the CNN with corresponding activation functions. Then, constructing the hybrid network involves reconstructing a phase space corresponding to $P(t)_l$ corresponding to time series data segment of length l to obtain a recurrence plot (RP). In the next step, a recurrence matrix, R_{ij} is obtained, defined as $R_{ij} = \|X_i - X_j\|$, where X_i and X_j represent

state points of the operational state in reconstructed phase space at i^{th} and j^{th} instances in time. In the next step, RPs corresponding to stable and unstable operational states. Then, the convolutional neural network (CNN) is trained using the RPs for known stable and unstable states. The trained CNN is then used to assign probabilities to unknown time series data segment as to stability of the operational state μ_i .

[0014] This and other aspects are described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawings, in which:

[0016] FIG. 1 shows schematic diagram of a system for predicting oscillatory instabilities in turbulent flow equipment according to embodiments of the invention.

[0017] FIG. 2A illustrates a method of predicting and mitigating impending onset of instabilities in turbulent flow equipment.

[0018] FIG. 2B illustrates steps in prediction using a neural ordinary differential equation (ODE) method.

[0019] FIG. 2C illustrates steps of a hybrid convolutional neural network according to embodiments of the invention.

[0020] FIG. 3A shows the time series of a system variable, SV_1 and FIG. 3B shows corresponding stability measure μ_1 , which is the distance of weight matrix from $W^{(r)}$, that approaches zero as oscillatory instability is approached.

[0021] FIG. 4A shows time series of a system variable (SV_2) as a function of control parameter CP_2 . FIG. 4B shows the stability measure μ_2 approaching 1 as the system transitions to oscillatory instability.

[0022] FIG. 5A shows system variable (SV_3) as a function of control parameter CP_3 . FIG. 5B shows that the stability measure μ_3 approaches 1 as the system transitions to oscillatory instability.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0023] While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material to the teachings of the invention without departing from its scope.

[0024] Throughout the specification and claims, the following terms take the meanings explicitly associated herein unless the context clearly dictates otherwise. The meaning of "a", "an", and "the" include plural references. The meaning of "in" includes "in" and "on." Referring to the drawings, like numbers indicate like parts throughout the views. Additionally, a reference to the singular includes a reference to the plural unless otherwise stated or inconsistent with the disclosure herein.

[0025] The present invention in its various embodiments is directed to systems, devices and methods for predicting the onset of oscillatory instabilities in turbulent flow systems.

[0026] One embodiment of a system for predicting oscillatory instabilities in turbulent flow equipment is illustrated with reference to FIG. 1. The system **100** comprises a sensor array **102** connected to an operating equipment **S**, wherein the sensor array is configured to measure one or more parameters of the system. In various embodiments, the operating unit **S** may be a thermoacoustic equipment, an aeroacoustic equipment or an aeroelastic equipment. The parameter may include pressure in some embodiments. In some embodiments, the sensor array **102** may comprise piezoelectric pressure transducers. In some embodiments the sensor array **102** may comprise a microphone. In some embodiments the sensor array **102** may comprise a strain gauge. The system further comprises a signal conditioner **108** for de-noising the signal before sending to an analog to digital converter **128** for converting the analog signals to machine-readable digital signal.

The system includes an analyzing unit **104**, configured to estimate a state tensor or matrix including multidimensional data from the digital signal.

[0027] The system in various embodiments includes a learning and prediction unit **130** configured for classifying and recognizing patterns present in multidimensional data to identify a state of the equipment. The state may, in some embodiments be characterized by one or more parameters indicating stability of the equipment **S**. In some embodiments, the parameters may either indicate stable operation or impending oscillatory instability. The system further includes an actuator array **112** configured to implement a control action to promote stable operation of the equipment **S**.

[0028] In various embodiments, the invention discloses methods of predicting and mitigating occurrence of a potentially unstable operating state of equipment. In one embodiment, a method **200** is disclosed with reference to FIG. 2A. The method comprises the steps of measuring in step **202**, by one or more sensors in a sensor array, a signal indicative of operating state of the equipment. In a second step **204**, the measured analog signal may be passed through a signal conditioner and converted, by analog to digital converter into a digital signal. In step **206**, a state tensor may be estimated from the digital signal by the analyzing unit. In the next step **208**, the state tensor is sent to a learning and prediction unit **130**. The prediction unit **130** configured with a neural network prediction module then receives the state tensor. The neural network prediction module may constitute a dynamic model of the operating state of the equipment. On feeding the received state tensor, the prediction module may calculate in step **210**, a stability parameter using the dynamic model. In some embodiments, the dynamic model may be updated (**212**) with the new state tensor data to improve the model.

[0029] In the next step, the method involves comparing the stability parameter **214** against a threshold to identify **216** likelihood of impending instability of the equipment. In various embodiments, the threshold is chosen appropriately according to permissible vibration

levels, vibration amplitude or pressure fluctuations in the equipment. In some embodiments, the method **200** may further involve further steps to mitigate the instability, as illustrated in FIG. 2B, sending the updated dynamic model to the analyzing unit in step **218**. The analyzing unit may then determine in step **220** an optimal path for control and the control action to mitigate the impending stability. The control action is then sent to the control unit by the analyzing unit in step **222**. In the final step **224**, the control action is implemented to modify the operating characteristics of the equipment. The modification in operating characteristics may move the equipment operating condition away from the impending instability, thereby avoiding damage to the equipment.

[0030] In some embodiments, the equipment is a thermoacoustic equipment or an aeroacoustic equipment and the actuator array **112** may comprise, cooling holes, staged fuel injectors, micro swirlers, water injectors or dampers. In some embodiments the dampers may comprise absorbent material fixed to the thermoacoustic equipment. The actuation may serve to move the resonance frequency away from the zone of instability. In some embodiments the equipment is an aeroacoustic equipment such as a wind turbine and the actuator array may comprise counterweights, fins, microthrusters, flying wheels or gyros. In some embodiments, the control action may involve modifying the resonance frequency of the equipment by actuating the counterweights, fins, microthrusters, flywheels or gyros. The actuator array **112** in some embodiments, may comprise a mechanical control of blade pitch. In some embodiments, the control action may involve modifying the blade pitch to reduce the instability. In some embodiments the equipment may be an aeroacoustic structure such as a bridge, or a high rise building, and the actuator array **112** may comprise counterweights. The control action may be to move the counterweights so that the resonance frequency is moved away from the frequency of operation.

[0031] In various embodiments, the method may involve using a neural ordinary differential equation (ODE) method to calculate one or more parameters characteristic of

the instability. In alternate embodiments, the method may involve using a hybrid convolutional neural network (CNN) for learning and prediction.

[0032] In various embodiments, the neural ODE method or the hybrid CNN may involve a neural network comprising several layers of nodes. In some embodiments, the neural networks may comprise at least 3 layers.

[0033] In various embodiments, the neural networks may make use of either supervised or unsupervised learning, or both to improve the prediction module. In some embodiments, the initial training may be using a supervised data set, and thereafter the prediction module may be configured to improve using unsupervised data.

[0034] In various embodiments, the neural ODE method **300** is described further with reference to FIG. 2B. The learning in the neural ODE method is equivalent to that of identification from a measured time series data, $p(t)$. The process involves constructing in step **301** a neural network (NN) with 3 or more layers, which maps the current dynamic state of the variable, $z(t)$ derived from $p(t)$, to its time derivative, $\dot{z}$. Here, the NN is equivalent to a matrix as in the state space representation which maps the state variables to their time derivative. The definition of the NN then involves in step **302**, defining the nodes in each layer and specifying a corresponding activation function. In the next step **304**, each node receives weighted inputs which are summed up and the activation function maps this sum to an output. The neural ordinary differential equation (ODE) is defined as,

$$\dot{z} = f(z, t, w)$$

Here w is the weight matrix of NN . The next step **306** involves computing the sum of the weighted inputs at each node for initial time t_0 and to a time instance t_1 for the corresponding states of the system, to obtain a weight matrix. If t_0 is the initial time instance, t_1 is the final time instance, and the corresponding operational states of the equipment are $z(t_0)$ and $z(t_1)$, the final state predicted by neural ODE, $z_p(t_1)$ is,

$$z_p(t_1) = \int_{t_0}^{t_1} f(z(t), t, w) dt$$

wherein the error in the prediction is given by,

$$J = \left(z(t_1) - z_p(t_1) \right)^2$$

The next step **308** involves computing a distance in the weight matrix defined as

$d^{(i)} = |\bar{w}^{(i)} - w^{(r)}|$, where $w^{(r)}$ is an average weight corresponding to an unstable state. In a final step **310**, the method involves computing a sum of the distances and obtain a parameter μ_1 that characterizes stability of the system. The parameter μ_1 may vary inversely as the sum, to obtain a measure of stability of the system.

[0035] In various embodiments, the method may further comprise training the neural network, prior to step **306**. Let, the i^{th} sample from experimental data correspond to $z(t)$ from t_i to $t_i + t_d$ duration. The neural ODE is trained on i^{th} sample data to get corresponding weights of NN as $w^{(i)}$. The time separation between successive samples ($t_{i+1} - t_i$) is t_s which is the stride size. The weights learned from the 1^{st} sample data i.e. $w^{(1)}$ is used as initial guess to find weights for subsequent samples. The weights are then averaged over a window of n_w samples, wherein an average weight $\bar{w}^{(i)}$ is given by

$$\bar{w}^{(i)} = \frac{1}{n_w} \sum_{j=(i-n_w+1)}^{j=i} w^{(j)}$$

The average weight corresponding to an unstable state ($w^{(r)}$) is used as reference to find the distance of an individual weight from it. The distance in the weight matrix is defined as,

$$d^{(i)} = |\bar{w}^{(i)} - w^{(r)}|$$

The distance $d^{(i)}$ almost remains constant for stable operation with small amplitude aperiodic pressure oscillations and starts linearly increasing as the operational state approaches instability. Here the distance is configured as a measure of operational stability, μ_1 . In various embodiments, the distances corresponding to the weight matrix

may be summed and μ_1 computed as an inverse function of the summed distance. In various embodiments of the disclosed method, variation of the parameter μ_1 approaching zero is used as a measure of the operational state approaching oscillatory instability.

[0036] Since the method **300** involves estimation of a Neural ODE characteristic of dynamic evolution of the operational state, the predictions of dynamic transitions upon variation of control parameters using the said method are expected to be more accurate than other methods of instability prediction. Thus the method **300** enables extrapolation or interpolation for operational states even in the control parameter space for which the prediction system was never trained. Thus, the neural ODE method may be trained using unknown data, or unsupervised learning.

[0037] In various embodiments, a hybrid convolutional neural network method **400** is described with reference to FIG. 2C. The hybrid method uses a recurrence plot along with convolution for neural prediction. The method comprises the steps of providing an input adjacency matrix of nodes in step **401**, and providing two or more convolutional layers with corresponding activation functions (**402**). The method then involves, constructing a recurrence plot (RP) from a time series segment, $P(t)_l$ of length l , corresponding to one of the state variables of the operational state. The pattern in the recurrence plot will vary according to the dynamics represented by $P(t)_l$. A recurrence plot is obtained in step **403** by first reconstructing the phase space corresponding to $P(t)_l$ following Takens' embedding theorem. In the next step, a recurrence matrix, R_{ij} is obtained (**404**), where $R_{ij} = \|X_i - X_j\|$, where X_i and X_j represents the state points of the operational state in the reconstructed phase space at i^{th} and j^{th} instances in time. $\| \cdot \|$ is an appropriate norm in various embodiments. In one embodiment, it may be an l^2 -norm. RPs are obtained as a plot representing R_{ij} . The method then involves in step **405** obtaining RPs corresponding to stable and unstable operational states. The unstable states may correspond to oscillatory instabilities, for example.

[0038] In the next step 406, RPs corresponding to stable state (aperiodic) and oscillatory instability (periodic) may be used to train the convolutional neural network to classify the operational state to stable and unstable conditions. The trained CNN, in turn, may be used (407) to assign probabilities for a time series segment of unknown stability state for it being an unstable state. These probabilities may be used as measures of stability of the operational state, μ_i . Use of the hybrid CNN method disclosed with reference to FIG. 2C, provides the ability to detect patterns in the multi-dimensional data and thus represent dynamical transition in operational state as transitions in patterns identified using the hybrid CNN method.

[0039] The systems devices and methods disclosed here have several advantages as further set forth herein. The neural network methods disclosed are robust and are configured to provide a multidimensional self-learning data-driven model of the dynamic transitions in equipment operation that exhibits oscillatory instability. They enable identification of optimal control path for variation of control parameters to ensure safe approach to a stable operational state. The multidimensional self-learning data driven model of the dynamic transitions in operational state is constructed in terms of a linear or nonlinear combination of a set of precursors of the onset of oscillatory instability known as the state tensor. The state tensor is a function of control parameters and during operation of the equipment, an evolving multidimensional map of the state tensor is constructed. When the device detects an undesirable dynamic state or the proximity to an undesirable dynamic state by examining the state tensor, it identifies an optimal manifold in the parameter space through which the equipment may be maneuvered to approach a stable operational state. Thus, the devices and methodology described in the embodiments not only provide precursors to the onset of oscillatory instabilities but also identify an optimized control action to approach a stable state of operation.

[0040] While the invention has been disclosed with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and

equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt to a particular situation or material the teachings of the invention without departing from its scope. Further, the examples to follow are not to be construed as limiting the scope of the invention which will be as delineated in the claims appended hereto.

[0041] EXAMPLES

[0042] Example 1: Neural ODE Method

[0043] The, thermoacoustic system was represented using the differential equation

$$\frac{dX_{pq}(t)}{dt} = f(X_{pq}(t), t, \theta)$$

We used neural ODE to approximate this mapping of state vector to its time derivative. On training the neural ODE on time series of p' and q , we get a model for the thermoacoustic system. The absolute value of the difference between the predicted and the true time series is used as loss function. Optimization of the average loss function with q gives the parameter vector for the neural ODE. Since the neural ODE is trained on time series representing the simultaneous variation of p' and q , a NN with the optimum q can represent the coupled behavior of the unsteady heat release rate and acoustic perturbations in the thermoacoustic system.

[0044] The variation of a system parameter SV_I with a parameter CP_1 of a combustor exhibiting thermoacoustic instability up on variation of CP_1 is shown in FIG. 3A. The corresponding variation of stability parameter μ_1 is illustrated in FIG. 3B. μ_1 approaching zero implies that the system is approaching oscillatory instability, and the progressive increase in amplitude of oscillation with decrease of μ_1 is observed to lead up to the instability.

[0045] Example 2: Convolutional Neural Network Method

[0046] The complete structure of the CNN used in the present study is detailed in Table I.

TABLE I. Structure of the CNN

Name	Dimensions	Operations
Input Adjacency Matrix	122×122	None
Conv-1	120×120×32	3×3×32 Convolution
Activation-1	120×120×32	ReLU Activation
MaxPool-1	60×60×32	2x2 Max Pooling
Conv-2	58×58×32	3×3×32 Convolution
Activation-2	58×58×32	ReLU Activation
MaxPool-2	29×29×32	2x2 Max Pooling
Flatten	26912	Converting to one column vector
FC-1	64	64 Fully-Connected
Activation-3	64	ReLU Activation
FC-2	1	1 Fully-Connected
Activation-4	1	Sigmoid Activation

[0047] In FIG. 4A-4B and FIG. 5A-5B, we show the variation of dynamics of a system where up on variation of two different control parameters CP_2 and CP_3 , as the systems approach oscillatory instability, the stability parameters μ_2 and μ_3 approach one.

What is claimed is:

1. A system for predicting and controlling onset of oscillatory instability in a turbulent flow equipment, the system comprising:
 - a sensor array comprising at least one sensor of a piezoelectric pressure transducer, a microphone or a strain gauge to measure analog signals;
 - an analog to digital converter for converting the analog signals to a digital signal;
 - an analyzing unit, configured to estimate a state tensor including multidimensional data from the digital signal, or to implement a control action to promote stable operation of the equipment; and
 - a learning and prediction unit configured for classifying and recognizing patterns present in multidimensional data to identify potential onset of an unstable operating state of the equipment.
2. The system of claim 1, further comprising an actuator array present on the equipment, the actuator array configured to implement the control action to promote a stable operating state of the equipment.
3. The system of claim 2, wherein the equipment is a thermoacoustic equipment, an aeroacoustic equipment or an aeroelastic equipment.
4. The system of claim 3, wherein the equipment is a thermoacoustic or an aeroacoustic equipment, and the actuator array comprises one or more of cooling holes, staged fuel injectors, micro swirlers, water injectors, or dampers.
5. The system of claim 3, wherein the equipment is an aeroelastic equipment, and the actuator array comprises counterweights, fins, micorhustors, flywheels or gyros.

6. A method of predicting and mitigating occurrence of a potentially unstable operating state of an equipment, the method comprising:

measuring, by one or more sensors in a sensor array, a signal indicative of operating state of the equipment to obtain a measured signal;
converting, by analog to digital converter the measured signal into a digital signal;
estimating, by an analyzing unit, a state tensor from the digital signal;
receiving the state tensor at a learning and prediction unit, the unit having a neural network prediction module with a dynamic model of the operating state of the equipment;
calculating a stability parameter corresponding to the received state tensor using the dynamic model;
updating the dynamic model with the state tensor;
comparing the stability parameter against a threshold; and
identifying an impending onset of instability in the operating state of the equipment.

7. The method of claim 6, further comprising:

sending the updated dynamic model to the analyzing unit;
determining, by the analyzing unit an optimal path for control and control action to mitigate the impending stability;
sending the control action to a control unit; and
modifying, by the control unit via an actuator array, the operating state of the equipment to mitigate the impending instability.

8. The method of claim 6, wherein the neural network method is one of a neural ordinary differential equation (ODE) method, or a hybrid convolutional neural network method.

9. The method of claim 8, wherein the neural network is an ODE neural network and the method comprises:

- a) constructing a neural network (NN) with at least 3 layers, that maps state variables $p(t)$ of an operational state to a dynamic state variable $z(t)$ and to its time derivative $\dot{z}$, wherein $\dot{z} = f(z, t, w)$;
- b) defining the NN with nodes in each layer and specifying a corresponding activation function;
- c) receiving weighted inputs corresponding to time series data at times t ;
- d) computing sum of the weighted inputs at each node for initial time t_0 , to a final time instance t_1 for the corresponding operational states to obtain a weight matrix;
- e) computing a distance in the weight matrix defined as $d^{(i)} = |\bar{w}^{(i)} - w^{(r)}|$, wherein $\bar{w}^{(i)}$ is an averaged weight over a window of n_w samples, $w^{(r)}$ is an average weight corresponding to an unstable state; and
- f) computing a sum of the distances and obtain a parameter μ_1 that varies inversely as the sum, to obtain a measure of stability of the operational state.

10. The method of claim 9, wherein in step d) the final state predicted by neural ODE, $z_p(t_1)$ is given by:

$$z_p(t_1) = \int_{t_0}^{t_1} f(z(t), t, w) dt, \text{ wherein,}$$

an error in the prediction is given by:

$$J = \left(z(t_1) - z_p(t_1) \right)^2.$$

11. The method of claim 8, comprising, prior to step d) training the neural network using weights learned from a first sample data $w^{(1)}$ as initial guess to find weights for subsequent samples;

training the neural network on i^{th} sample data to get corresponding weights of NN as $w^{(i)}$; and

averaging the weights over a window of n_w samples,

$$\bar{w}^{(i)} = \frac{1}{n_w} \sum_{j=(i-n_w+1)}^{j=i} w^{(j)}.$$

12. The method of claim 8, wherein the neural network is a hybrid convolutional neural network (CNN) and the method comprises:

providing an input adjacency matrix of nodes to construct the convolutional neural network;

providing two or more convolutional layers in the CNN with corresponding activation functions;

reconstructing a phase space corresponding to $P(t)_l$ corresponding to time series data segment of length l to obtain a recurrence plot (RP);

obtaining a recurrence matrix, R_{ij} defined as $R_{ij} = \|X_i - X_j\|$, where X_i and X_j represent state points of the operational state in reconstructed phase space at i^{th} and j^{th} instances in time;

obtaining RPs corresponding to stable and unstable operational states;

training the convolutional neural network (CNN) using the RPs for known stable and unstable states; and

using the trained CNN to assign probabilities to unknown time series data segment as to stability of the operational state μ_i .

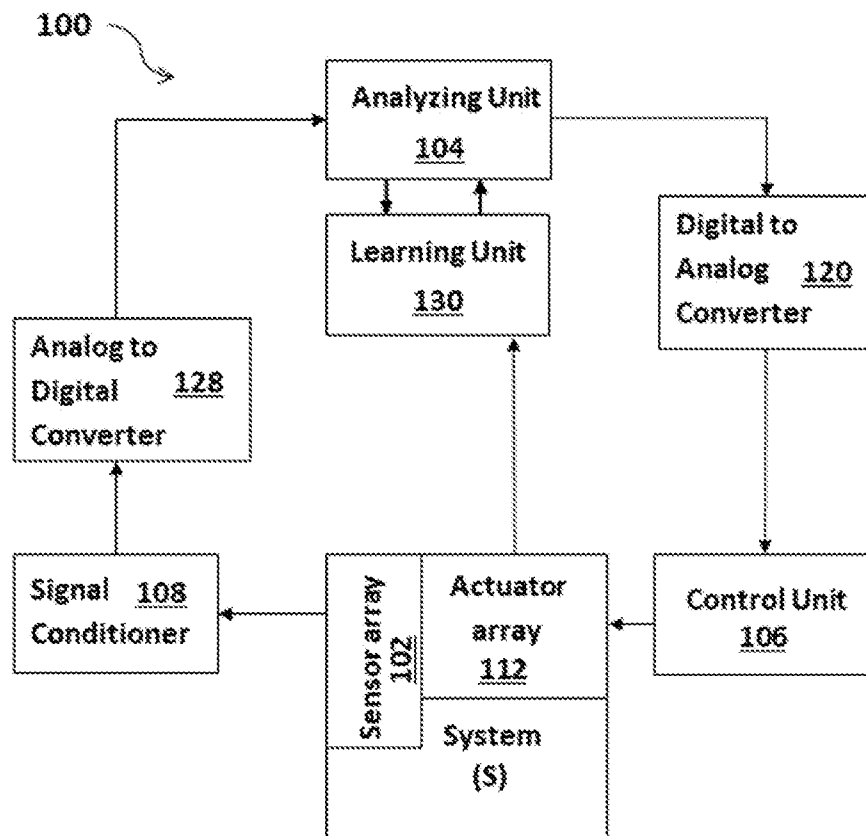


FIG. 1

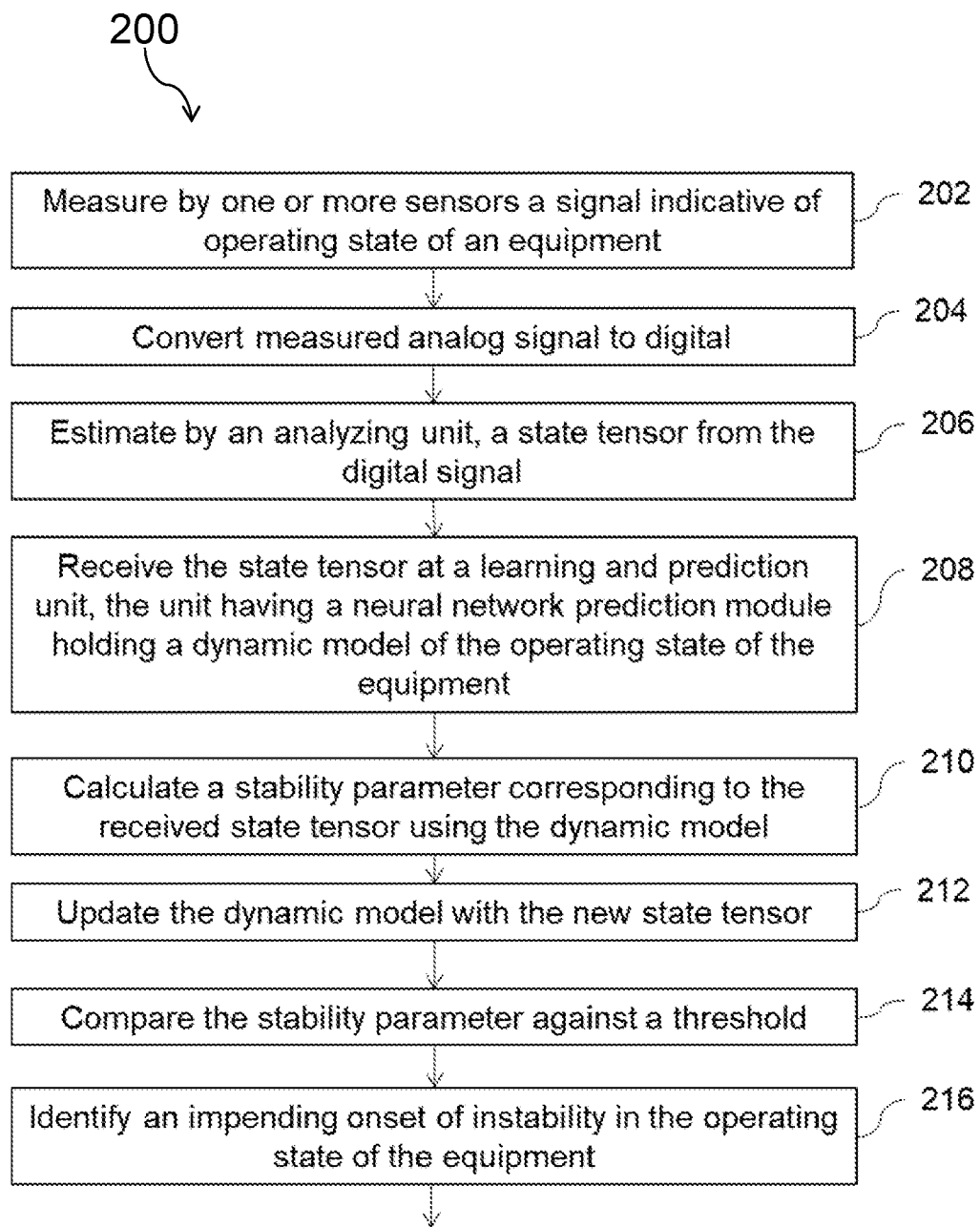


FIG. 2A...

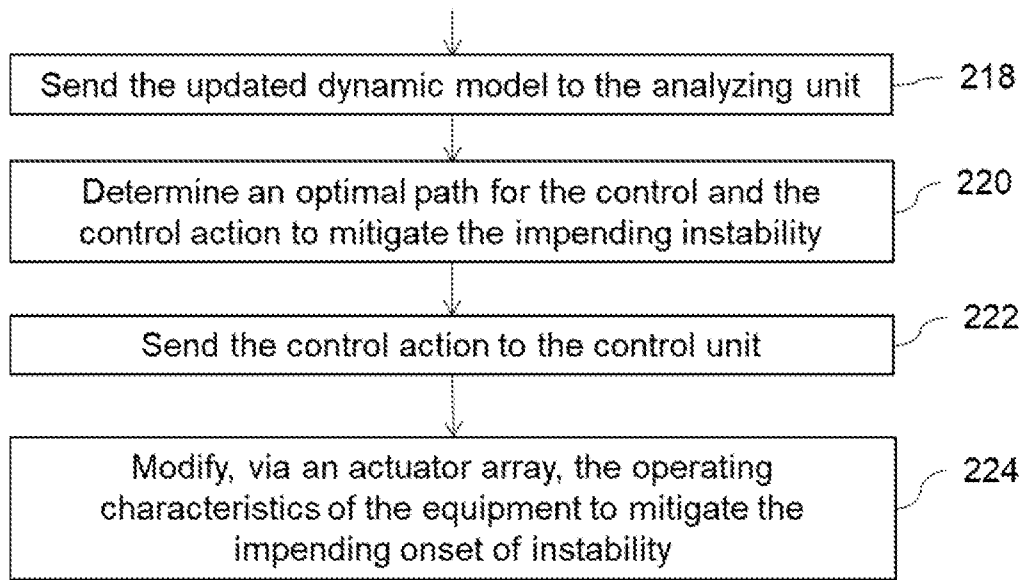


FIG. ...2A

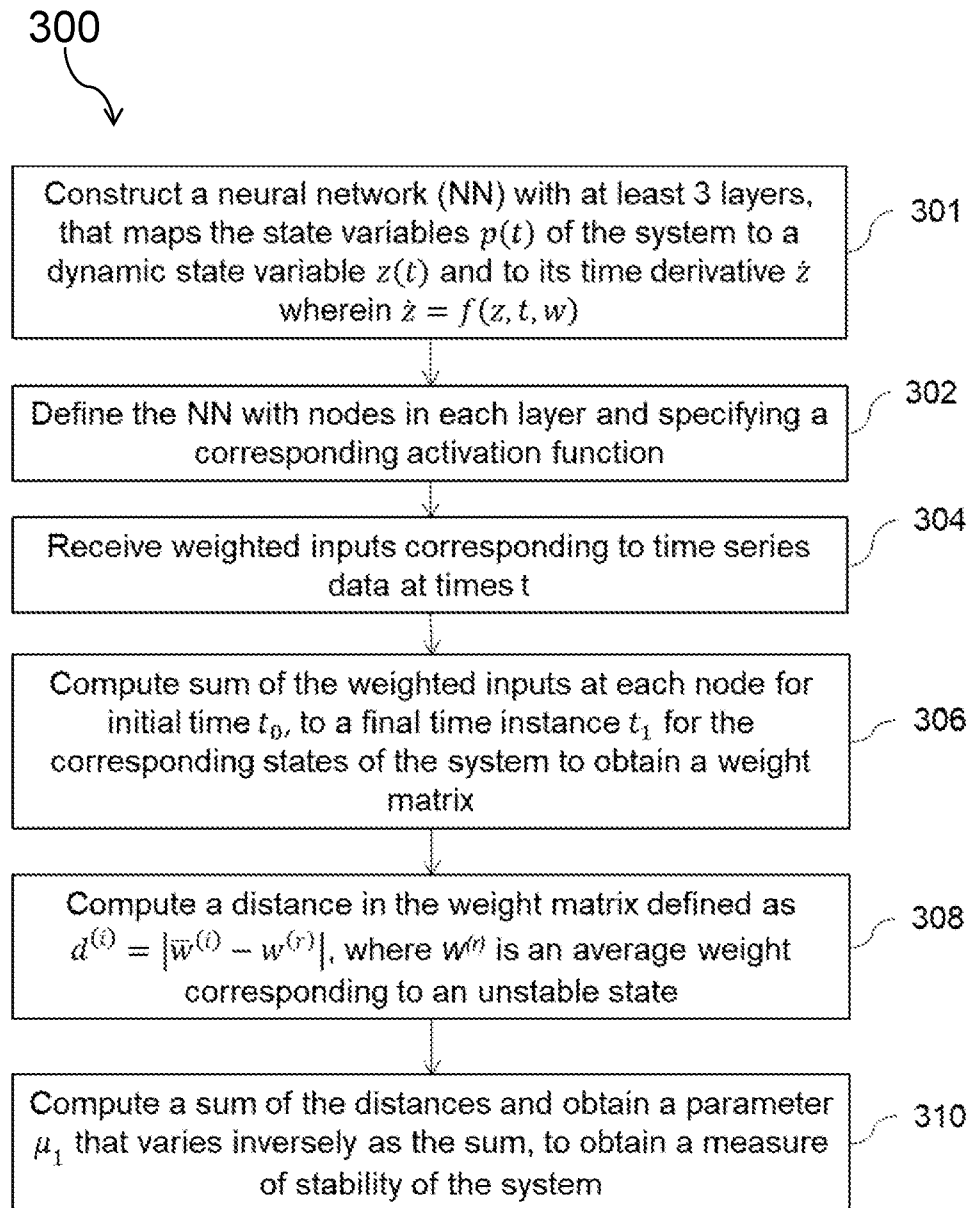


FIG. 2B

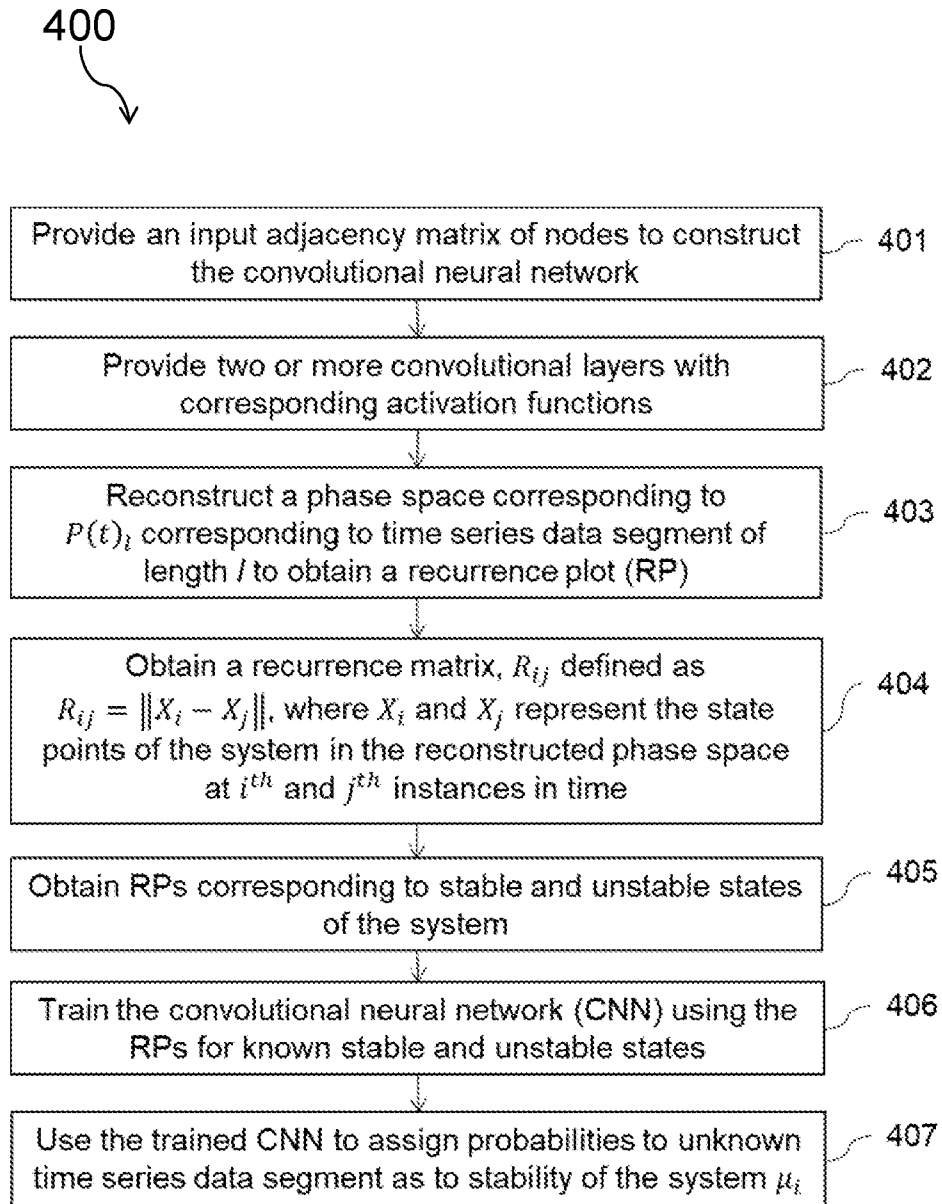


FIG. 2C



FIG. 3A

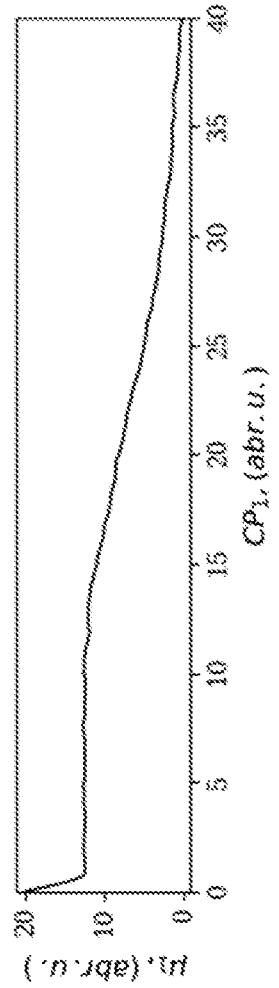


FIG. 3B

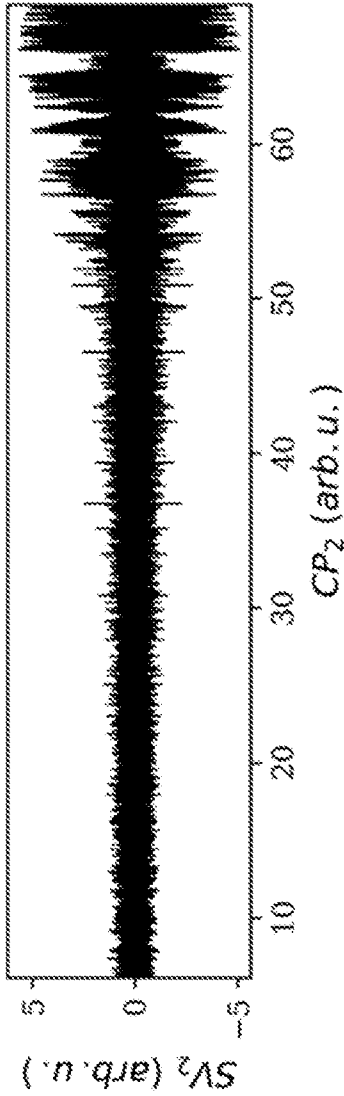


FIG. 4A

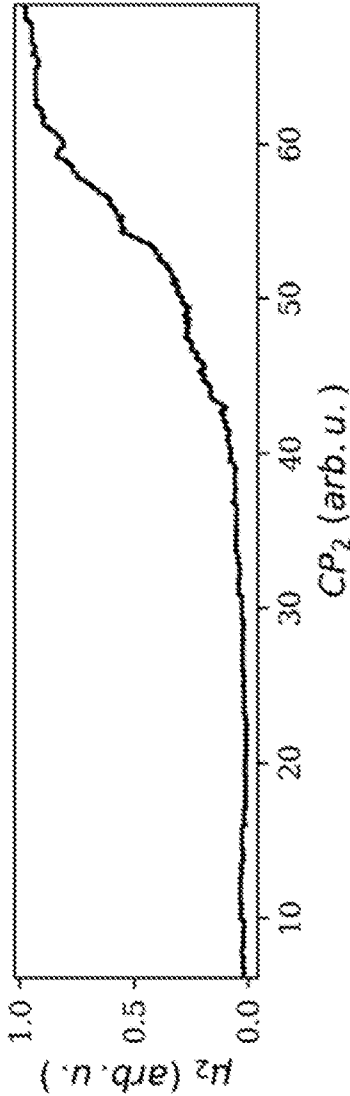


FIG. 4B

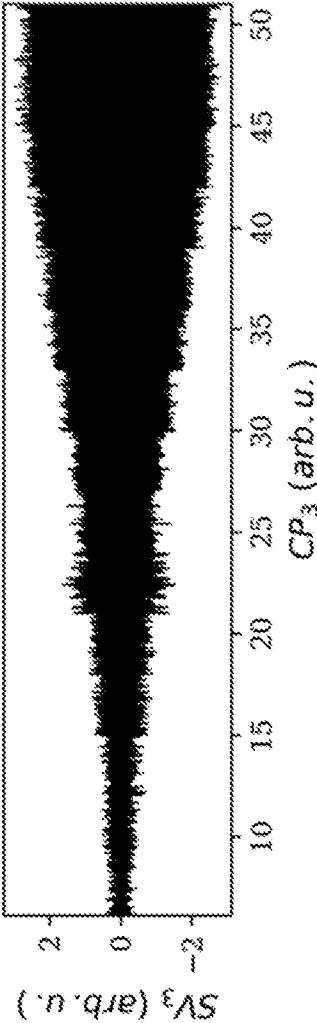


FIG. 5A

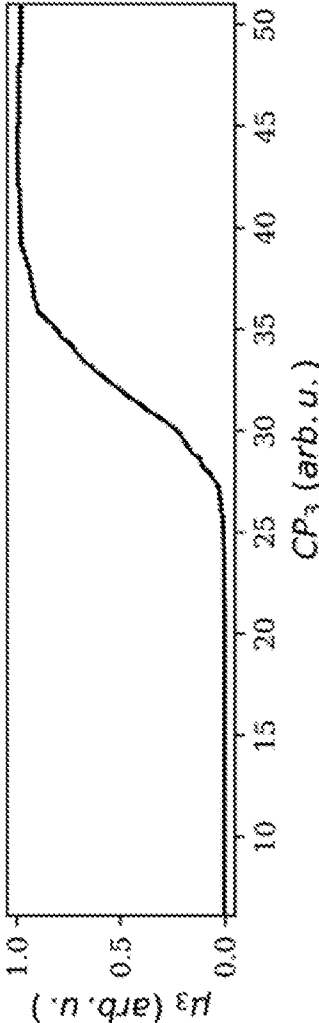


FIG. 5B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2021/056434

A. CLASSIFICATION OF SUBJECT MATTER

G01M13/028, G05B23/00, G05D19/00 Version=2021.01

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01M, G05B, G05D, G01H, G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Databases: PatSeer, IPO Internal Database.

Keywords: oscillatory instabilities, turbulent flow.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2018198132 A1 (INDIAN INSTITUTE OF TECHNOLOGY MADRAS) 1st November 2018 (01.11.2018). Abstract; Paragraphs [0010]-[0015], [0019]-[0034]; Claims 1, 6.	1-12
Y	US 5784300 A (GEORGIA TECH RESEARCH CORPORATION) 21st July 1998 (21.07.1998). Entire document.	1-12

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

25-10-2021

Date of mailing of the international search report

25-10-2021

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IB2021/056434

Citation	Pub.Date	Family	Pub.Date
WO 2018198132 A1	01-11-2018	US 2021132555 A1	06-05-2021
		IN 201741014957 A	02-11-2018
US 5784300 A	21-07-1998	US 5719791 A	17-02-1998