Higgs mechanism and the added-mass effect

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In the Higgs mechanism, mediators of the weak force acquire masses by interacting with the Higgs condensate, leading to a vector boson mass matrix. On the other hand, a rigid body accelerated through an inviscid, incompressible and irrotational fluid feels an opposing force linearly related to its acceleration, via an added-mass tensor. We uncover a striking physical analogy between the two effects and propose a dictionary relating them. The correspondence turns the gauge Lie algebra into the space of directions in which the body can move, encodes the pattern of gauge symmetry breaking in the shape of an associated body and relates symmetries of the body to those of the scalar vacuum manifold. The new viewpoint is illustrated with numerous examples, and raises interesting questions, notably on the fluid analogues of the broken symmetry and Higgs particle, and the field-theoretic analogue of the added mass of a composite body.

1. Introduction

In the recently confirmed [1,2] Higgs mechanism [3–6], the otherwise massless carriers of the weak force (\(W^\pm, Z\) gauge bosons) acquire masses by interacting with the Higgs medium. It is tempting to look for analogies where a body gains mass while moving through a fluid, to complement standard examples of (Abelian) mass generation for photons in a superconductor or plasma. Fluid analogies are often unsatisfactory, as they suggest resistive effects which are not present in the Higgs mechanism. However, McClements & Thyagaraja [7] recently pointed out that a dissipationless fluid analogue for the Higgs mechanism is provided by the added-mass effect. In its essence, this effect goes at least as far back as Green and Stokes (see Art. 92 in [8]). To impart an acceleration \(a = \dot{U}(t)\) to a body of mass \(m\) immersed in an inviscid, incompressible and irrotational fluid, one must apply a force exceeding \(ma\), as energy must also be pumped into the induced
fluid flow. The added force $F^\text{add}_i = \mu_{ij} \dot{q}_j(t)$ is proportional to the acceleration, but could point in a different direction, as determined by the added-mass tensor $\mu_{ij}$. $\mu_{ij}$ depends on the fluid and shape of the body, but not on its mass distribution, unlike its inertia tensor. For example, the added-mass tensor of a sphere is $\delta_{ij}$ times half the mass of displaced fluid. So an air bubble accelerated in water ‘weighs’ about $\rho_{\text{water}}/2 \rho_{\text{air}} \approx 400$ times its actual mass. The added-mass effect is different from buoyancy: when the bubble is accelerated horizontally, it feels a horizontal opposing acceleration reaction force $\mathbf{G} = -\mathbf{F}^\text{add}$ aside from an upward buoyant force which is independent of $\mathbf{a}$ and equal to the weight of fluid displaced.

Here, we develop a novel and precise physical analogy between the added-mass and Higgs mechanisms. It is not a mathematical duality like the high temperature–low temperature Kramers–Wannier duality in the Ising model or the AdS/CFT (anti-de Sitter space conformal field theory) gauge-string duality, but provides a fascinatingly new viewpoint on fluid-mechanical and gauge-theoretic phenomena. We discover a way of associating a rigid body to a pattern of spontaneous symmetry breaking (SSB). We call this the Higgs added-mass (HAM) correspondence, it applies to both Abelian and non-Abelian gauge models. Consider a $(3 + 1)$-dimensional Yang–Mills theory with $d$-dimensional gauge group $G$, which spontaneously breaks to a subgroup $H$ when coupled to scalars $\phi$ in a specified representation of $G$, subject to a given $G$-invariant potential $V$. The correspondence relates this to a rigid body accelerated (for simplicity) through a non-relativistic, inviscid, incompressible (constant density) irrotational fluid which is asymptotically at rest in $\mathbb{R}^d$. The Lie algebra $\mathfrak{g}$ plays the role of the space through which fluid flows (with the location of the body as the origin). In particular, the $(3 + 1)$ space–time dimension of the gauge theory is unrelated to $d$. The fluid is the analogue of the scalar field, while the rigid body plays the role of the vector bosons. Moreover, we propose a fluid analogue for the Higgs particle. The correspondence proceeds through the respective mass matrices, and relates symmetries on either side, as exemplified by numerous examples that we present.

We begin this paper in §2 with a description of the added-mass effect, followed in §3 with a brief statement of the correspondence and several examples of SSB patterns and their corresponding rigid bodies. In each case, rotation and reflection symmetries of the body are related to symmetries of $G/H$, endowed with a metric implied by the vector boson mass matrix. Based on these examples, we present, in §4, a detailed dictionary relating various quantities/phenomena on either side of the correspondence. The reader interested in a summary of the correspondence may start with §4. We conclude in §5 with a discussion of interesting questions that the new viewpoint raises.

## 2. The added-mass effect

Perhaps the simplest example of the added-mass effect is in one-dimensional flow. Consider an arc-shaped rigid body of length $L$ surrounded by an ideal fluid filling the circumference of a circle of radius $R$. Incompressibility $\partial_t v(\theta, t) = 0$ along with impenetrability of the body imply that the flow velocity $v$ everywhere is the same as that of the body $v = U(t)$. The rate of increase in flow kinetic energy

$$\frac{d}{dt} \int_\text{fluid} \frac{1}{2} \rho v^2 R d\theta = \rho (2\pi R - L) U \dot{U}$$

must equal the power supplied by the added force $F^\text{add} U(t)$. Thus, $F^\text{add}$ is proportional to the acceleration of the body, which gains an added-mass $\mu = \rho (2\pi R - L)$. $\mu$ being equal to the total mass of fluid is peculiar to this one-dimensional toy model; this is why we choose a circular flow domain instead of the whole real line.

More generally, following Batchelor [9], consider incompressible (constant density) three-dimensional potential flow around a simply connected rigid body executing purely translational motion at velocity $\mathbf{U}(t)$ (see appendix B for extension to compressible flows). We restrict ourselves to the case where external forces do not cause the body to rotate. The fluid, assumed asymptotically at rest, has velocity $\mathbf{v} = \nabla \phi$ with $\nabla \cdot \mathbf{v} = \nabla^2 \phi = 0$. $\phi$ is determined by
impenetrability: \( \nabla \phi \cdot n = U(t) \cdot n \), where \( n \) is the unit outward normal on the body’s surface \( A \).

The boundary condition constrains \( \phi \) to be linear in \( U \), which allows us to write \( \phi(r) = U \cdot \Phi(r) \),

where we call \( \Phi(r) \) the potential vector field. \( \Phi(r) \) depends on the shape of the body, but not on its velocity \( U \). As time progresses, \( \Phi = \Phi(r - r_0(t)) \), where \( r_0(t) \) is a convenient reference point in the body. For a sphere of radius \( a \) instantaneously centred at the origin,

\[
\phi(r) = -\frac{a^3}{2r^3} U(t) \cdot r \quad \text{and} \quad \Phi = -\frac{a^3}{2} \frac{\dot{r}}{r^2}.
\]

Bernoulli’s equation,

\[
p + \frac{1}{2} \rho v^2 + \rho \frac{\partial \phi}{\partial t} = \text{const.}(t),
\]

allows us to express the total pressure force on the body as

\[
F = -\int_A p n \, dA = \rho \int_A \left( \frac{\partial \phi}{\partial t} + \frac{1}{2} v^2 \right) n \, dA.
\]

Using the factorization \( \phi = U \cdot \Phi \), we write \( F \) as a sum of an acceleration reaction force \( G \) and an acceleration-independent \( G' \)

\[
F = \rho \int_A U \cdot \Phi n \, dA + \int_A \left[ \frac{1}{2} \rho v^2 - \rho U \cdot v \right] n \, dA \equiv G + G'.
\]

\( G' \) vanishes in fluids asymptotically at rest in \( \mathbb{R}^3 \) [9]. Using a multipole expansion for \( \phi \) (see appendix A), one estimates that \( G' \) can be at most of order \( 1/R \) in a large container of size \( R \). It is as if fluid can hit the container and return to push the body. We ignore this boundary effect. When acceleration owing to gravity \( g \) is included, \( G' \) features a buoyant term \( -\rho V_{\text{body}} g \) equal to the weight of fluid displaced, which we suppress. Thus, the acceleration reaction force is

\[
G_i = -\mu_{ij} U_j, \quad \text{where} \quad \mu_{ij} = -\rho \int_A \Phi_j n_i \, dA.
\]

The added-mass tensor \( \mu_{ij} \) is a direction-weighted average of the potential vector field \( \Phi \) over the body surface. It is proportional to the fluid density and depends on the shape of the body surface. \( \mu_{ij} \) may be shown to be time-independent and symmetric. The rate at which energy is pumped into the fluid is \( -G \cdot U(t) = \mu_{ij} U_i U_j(t) \). Thus, the flow kinetic energy may be expressed entirely in terms of the body’s velocity and added-mass tensor (it follows that the added-mass tensor \( \mu_{ij} \) is a positive matrix):

\[
\frac{1}{2} \int_V \rho v^2 \, dV = \frac{1}{2} \mu_{ij} U_i U_j.
\]

To a particle physicist, mass generation in a medium sounds like the Higgs mechanism, and an added-mass tensor is reminiscent of a mass matrix. To uncover a precise correspondence between these phenomena, it helps to have explicit examples. By solving potential flow around rigid bodies, one obtains their added-mass tensors. We will relate these rigid bodies and their added-mass tensors to specific patterns of spontaneous gauge symmetry breaking. For a 2-sphere of radius \( a \), \( \mu_{ij} = \frac{2}{3} \pi a^3 \rho \delta_{ij} \) is isotropic. The added mass of a sphere is half the mass of fluid displaced, irrespective of the direction of acceleration. For an ellipsoid \( x^2/a^2 + y^2/b^2 + z^2/c^2 = 1 \), \( \mu_{ij} \) is diagonal in the principal axis basis. If \( a > b > c \), then the eigenvalues satisfy \( \mu_x < \mu_y < \mu_z \). Roughly, added mass grows with cross-sectional area presented by the accelerating body. In its principal axis basis [8]

\[
(\mu_x, \mu_y, \mu_z) = \frac{4}{3} \pi abc \rho \left( \frac{\alpha}{2 - \alpha}, \frac{\beta}{2 - \beta}, \frac{\gamma}{2 - \gamma} \right),
\]

where

\[
a = abc \int_0^\infty (a^2 + \lambda)^{-1} \Delta^{-1} \, d\lambda, \quad \text{with} \quad \Delta = \sqrt{(a^2 + \lambda)(b^2 + \lambda)(c^2 + \lambda)}
\]

and cyclic permutations thereof. In particular, for an ellipsoid of revolution with \( a = b \), the corresponding pair of added-mass eigenvalues coincide, \( \mu_x = \mu_y \). On the other hand, by taking
c → 0 we get an elliptic disc, for which two added-mass eigenvalues \( \mu_x \) and \( \mu_y \) vanish. These correspond to acceleration along its plane. With impenetrable boundary conditions, an elliptic disc does not displace fluid or feel an added mass when accelerated along its plane. The third eigenvalue \( \mu_z \), for acceleration perpendicular to its plane, is \( \frac{4}{3} \pi \rho a b^2 E(1 - b^2/a^2)^{-1} \), where \( E(m) \) is the complete elliptic integral of the second kind. Taking \( a = b \), the principal added masses of a circular disc are \((0, 0, (8/3) \rho a^3)\). Shrinking the elliptical disc further, a thin rod of length \( 2a \) has no added mass. Irrespective of which way it is moved, it does not displace fluid with impenetrable boundary conditions. The same is true of a point mass or any body whose dimension is less than that of the flow domain by at least two (co-dimension ≥ 2). For an infinite right circular cylinder, the added mass per unit length for acceleration perpendicular to its axis is equal to the mass of fluid displaced. If the axis of the cylinder is along \( z \), then the added-mass tensor per unit length is \( \mu_{ij}/L = \pi a^2 \rho \text{diag}(1, 1, 0) \), where \( a \) is its radius. Although these examples pertain to three-dimensional flows, the added-mass effect generalizes to rigid bodies accelerated through plane flows as well as flows in four and higher dimensions. The case of plane flow is well known and treated, for instance, in [9]. For example, an elliptical disc with semi-axes \( a, b \) accelerated through planar potential flow has an added-mass tensor \( \mu_{ij} = \pi \sigma a b \delta_{ij} \), where \( \sigma \) is the (constant) mass of fluid per unit area. In appendix A, we develop the formalism for the added-mass effect in \( d \geq 3 \) dimensions. This will be used in the following sections where we relate the added-mass effect in \( d \)-dimensional flows to spontaneous breaking of a \( d \)-dimensional gauge group \( G \).

3. Spontaneous symmetry breaking patterns and their rigid bodies

In the simplest version of the Higgs mechanism, a \( G = U(1) \) gauge field \( A \) in \((3 + 1)\) space–time dimensions is coupled to a complex scalar \( \phi \) with potential \( V(\phi) = -m^2 |\phi|^2 + \lambda |\phi|^4 \) and Lagrangian

\[
\mathcal{L} = \frac{1}{2} (\mathbf{E}^2 - \mathbf{B}^2) + |(\partial_\mu - igA_\mu)\phi|^2 - V(\phi).
\]

The space of scalar vacua \( \mathcal{M} \) (global minima of \( V \)) is a circle of radius \( \eta = \sqrt{m^2/2\lambda} \). If \( U(1) \) were a global symmetry, we would have one angular Goldstone mode. A non-zero vacuum expectation value (VEV) \( \langle \phi \rangle = \eta \) leads to complete spontaneous breaking of the symmetry group \( G \). If \( \phi = (\eta + \rho) e^{i\chi/\eta} \), we may gauge away \( \chi \) and get a mass term \( g^2 \eta^2 A^2 \) for the photon (which has ‘eaten’ the Goldstone mode), and a radial scalar mass term \( m^2 \rho^2 \) corresponding to the Higgs particle. In general [10], \( G \) breaks to a residual symmetry group \( H \) whose generators annihilate the vacuum and \( g^2 \eta^2 A^2 \) is replaced by gauge boson mass terms \( \frac{1}{2} M_{ab} A^a A^b \). We say that a spontaneously broken gauge theory corresponds to a rigid body, if vector boson masses and added-mass eigenvalues coincide. In particular, the dimension of \( G \) must equal that of the flow domain. We begin with some examples of SSB patterns and associated rigid bodies. In these examples, the space of scalar vacua \( \mathcal{M} \) is the quotient \( G/H \). They reveal a relation between symmetries of \( G/H \) and of a corresponding ideal rigid body. By an ideal rigid body, we mean one with maximal symmetry group among those with identical added-mass eigenvalues: for example, a round sphere of appropriate radius, instead of a cube.

Consider an SO(3) gauge theory minimally coupled to a triplet of real scalars interacting via the above potential \( V \). \( \mathcal{M} \) is a 2-sphere of radius \( \eta \) resulting in two Goldstone modes. They are eaten by two of the three gauge bosons leaving one massless photon. The mass-squared matrix \( M \) is \( 2g^2 \eta^2 \text{diag}(1, 1, 0) \). \( G = \text{SO}(3) \) breaks to \( H = \text{SO}(2) \). The corresponding rigid body moves in fluid filling three-dimensional Euclidean space, as \( \text{dim } G = 3 \). The rigid body must have one zero and two equal added-mass eigenvalues to correspond to the mass matrix \( M \). An ideal rigid body that does the job is a hollow cylindrical shell, say \( S^1 \times [-1, 1] \). Such a shell has no added mass when accelerated along its axis. Owing to its circular cross-section, the added masses are equal and non-zero for acceleration in all directions normal to the axis.
— Similarly, an $O(n)$ gauge theory coupled to $n$-component real scalars spontaneously breaks to $H = SO(n - 1)$. The vacuum manifold $M$ is a sphere $S^{n-1}$ of radius $\eta$. We get $n - 1$ vector bosons of mass $\sqrt{2}\eta n$ and $n_v = (n - 1)(n - 2)/2$ massless photons. A corresponding ideal rigid body moving through fluid filling $\mathbb{R}^{1/2}(n^2 - n)$ is the product $S^{n^2 - 2} \times B^{n_v}$, generalizing the cylindrical shell $S^1 \times B^1$ when $n = 3$. Here $B^{n_v}$ is a unit ball $|x| \leq 1$ for $x \in \mathbb{R}^{n_v}$. This ideal rigid body has equal non-zero added masses when accelerated along the first $n - 1$ directions and no added mass in the remaining $n_v$ flat directions. We call $S^{n^2 - 2}$ its curved factor and the unit ball $B^{n_v}$ its flat factor. $B^1$ is the unit interval while $B^2$ is the unit disc, etc. It is easily seen that, for $n = 3$ and 4, acceleration along the direction of the interval or in the plane of the disc displaces no fluid; the same holds for $n \geq 5$.

— For $SU(2)$ gauge fields coupled to a complex scalar doublet with the same potential $V$, $M$ is the product of $SU(2)$ broken to $SU(2)$ and a $U(1)$ gauge theory coupled to a complex scalar with charge $\eta$. Similarly, an $SO(n)$ gauge field couples a complex scalar with the same potential $V$. The corresponding ideal rigid body moves through fluid filling $\mathbb{R}^{1/2}(n^2 - n)$ is the product $S^{n^2 - 2} \times B^{n_v}$, generalizing the cylindrical shell $S^1 \times B^1$ when $n = 3$. Here $B^{n_v}$ is a unit ball $|x| \leq 1$ for $x \in \mathbb{R}^{n_v}$. This ideal rigid body has equal non-zero added masses when accelerated along the first $n - 1$ directions and no added mass in the remaining $n_v$ flat directions. We call $S^{n^2 - 2}$ its curved factor and the unit ball $B^{n_v}$ its flat factor. $B^1$ is the unit interval while $B^2$ is the unit disc, etc. It is easily seen that, for $n = 3$ and 4, acceleration along the direction of the interval or in the plane of the disc displaces no fluid; the same holds for $n \geq 5$.

— In unbroken gauge theories, all gauge bosons remain massless. Such a theory with a $d$-dimensional gauge group corresponds to a point particle (or one of co-dimension $> 1$) moving through $\mathbb{R}^d$, which has no added mass. For instance, $SU(2)$ coupled to a complex scalar triplet in the potential $V = m^2 \phi^2 + \lambda|\phi|^4$ moves with $m^2 > 0$ remains unbroken and corresponds to a point particle moving through $\mathbb{R}^3$.

— $SU(3)$ with fundamental scalars breaks to $SU(2)$ and $M = S^3$. There are three massless photons, four vector bosons of mass $g\eta/\sqrt{2}$ and a heavier singlet of mass $\sqrt{2}g\eta/\sqrt{3}$. The corresponding ideal rigid body moves in $\mathbb{R}^8$. Its curved factor is a four-dimensional ellipsoid $\sum_{i=1}^4(x_i^2/a_i^2) + x_5^2/b^2 = 1$ with $b < a$. The unit ball $B^3$ is its flat factor, which gives rise to three vanishing added-mass eigenvalues $\mu_5 = \mu_6 = \mu_7 = 0$. Acceleration along the first five coordinates $x_1, \ldots, x_4, x_5$ leads to added-mass eigenvalues $\mu_1 = \cdots = \mu_4 < \mu_5$ as the semi-axes satisfy $a > b$ (higher added mass when larger cross-section presented).

— A $U(1)$ gauge theory coupled to a complex scalar with charge $g\eta$ ($\phi \to e^{i\eta\theta}(\phi)$ breaks completely in the above potential $V$, leaving one vector boson with mass $\sqrt{2}g\eta$. The corresponding rigid body can be regarded as an arc of a circle moving through fluid flowing around the circumference, as in §2. Another illustrative class of theories have $G = U(1)^d$ with couplings $g_{11}, \ldots, g_{dd}$ and $p$ complex scalars in a reducible representation ($p \leq d$ ensures all Goldstone modes are eaten). We assume the scalar $\phi_i$ has charge $q_{ik}$ under the $k$th $U(1)$ factor and transforms as $\phi_i \to e^{i\eta_k \theta_k}(\phi_i)$. They are subject to the potential $\sum_{i=1}^p(-m_i^2|\phi_i|^2 + \lambda_i|\phi_i|^4)$. If $\eta_i = (m_i^2/2\lambda_i)^{1/2}$, the vacuum manifold is a $p$-torus, the product of circles of radii $\eta_i$: $M = S^1_{\eta_1} \times \cdots \times S^1_{\eta_p}$. There are $p$ Goldstone modes and the mass-squared matrix $M_{ab} = 2 \sum_{i=1}^p q_{ia} q_{ib} \eta_i^2$ is a sum of $p$ rank-1 matrices and generically has $d - p$ zero eigenvalues; $G = U(1)^d$ breaks to $U(1)^d - p$. A corresponding ideal rigid body moving in $\mathbb{R}^d$ generalizes the cylinder with elliptical cross-section. It is a product of a (curved) ellipsoid with a (flat) unit ball: $[\sum_{i=1}^p x_i^2/a_i^2] = 1 \times B^{d-p}$. For pairedwise unequal $a_i$, it has distinct non-zero added-mass eigenvalues when accelerated along $x_1, \ldots, x_p$ and none along its $d - p$ flat directions. For example, a $U(1)^3$ theory with a complex doublet in the above reducible representation breaks to $U(1)$. The corresponding rigid body is a cylinder with elliptical cross-section moving in $\mathbb{R}^3$. On the other hand, with three-component complex scalars, $U(1)^3$ completely breaks leaving three massive vector bosons with generically distinct masses. A corresponding ideal rigid body is an ellipsoid moving through fluid filling $\mathbb{R}^3$.

— It is interesting to identify the rigid body corresponding to electroweak symmetry breaking. Here $G = SU(2)_L \times U(1)_Y$ and $H = U(1)_Q$ with a massless photon and $m_{W^+} = \eta$.
$m_{W} < m_{Z}$. The corresponding rigid body must move through fluid filling $\mathbb{R}^{4}$ and have principal added masses $\mu_1 = \mu_2 < \mu_3$, $\mu_4 = 0$. An ideal rigid body generalizes a hollow cylinder. It is the three-dimensional hypersurface $\left\{ \sum_{i=1}^{3} x_i^2/a_i^2 = 1 \right\} \times [-1, 1]$ with $a_1 = a_2 > a_3 > 0$, embedded in $\mathbb{R}^{4}$. It has an ellipsoid of revolution as cross-section. When accelerated along $x_4$, it displaces no fluid, but has equal added masses when accelerated along $x_1$ and $x_2$.

More generally, we may associate an ideal rigid body to any pattern $G \rightarrow H$ of SSB, through its vector boson mass-squared matrix $M_{ab}$. $M_{ab}$ can always be block diagonalized into a $p \times p$ non-degenerate block (whose eigenvalues $m_1^2, \ldots, m_p^2$ are the squares of the masses of the massive vector bosons) and a $(d - p) \times (d - p)$ zero matrix corresponding to massless photons, where $\dim G = d$ and $\dim H = d - p$. A corresponding ideal rigid body is a product of curved and flat factors. To the non-degenerate part of $M_{ab}$, we associate a ‘curved’ $(p - 1)$-dimensional ellipsoid $x_1^2/a_1^2 + \cdots + x_p^2/a_p^2 = 1$. The semi-axis lengths $a_i$ are fixed by the vector boson masses. The ‘flat’ factor of the body can be taken as a $(d - p)$-dimensional unit ball $B_{d-p} : (x_{p+1}, \ldots, x_d | x_{p+1}^2 + \cdots + x_d^2 \leq 1)$. For $p = d - 1$, it is an interval, and for $p = d - 2$ it is a unit disc, etc. Motion along the flat directions $x_{p+1} \cdots x_d$ does not displace fluid, leading to $d - p$ zero added-mass eigenvalues while acceleration in the first $p$ directions leads to $p$ non-zero added-mass eigenvalues. If the vector boson masses are ordered as $0 < m_1 = m_2 = \cdots = m_{p_1} < m_{p_1+1} = \cdots = m_{p_1+p_2} < \cdots < m_{p-p_r+1} = \cdots = m_p$, then the corresponding semi-axes of the ellipsoid satisfy $0 > a_1 = a_2 = \cdots = \lambda_{p_1} > a_{p_1+1} = \cdots = a_{p_1+p_2} > \cdots > a_{p-p_r+1} = \cdots = a_p$ as the added mass grows with cross-sectional area presented. Here we have allowed for degeneracies among the masses, so that there are $r$ distinct non-zero masses with degeneracies $p_1, \ldots, p_r$ and $p = p_1 + \cdots + p_r$. To find an explicit formula for the semi-axes $a_i$ in terms of the vector boson masses and fluid density $\rho$, we would need to solve the potential flow equations around this rigid body.

(a) Symmetries of $G/H$ and of a rigid body

In all these examples, the ideal rigid body corresponding to a given pattern of symmetry breaking is a product of curved and flat factors, with added mass for acceleration along the former. The flat factor could be taken as an interval/disc/ball of dimension $\dim H$. The vacuum manifold $\mathcal{M} = G/H$ could be endowed with a non-degenerate metric determined by the vector boson mass-squared matrix $M_{ab}$, as, in all these examples, the number of Goldstone modes $p = \dim \mathcal{M}$ is equal to the number of massive vector bosons. $M_{ab}$ is in general degenerate, but may be block diagonalized into a non-degenerate $p \times p$ block and a zero matrix (corresponding to residual symmetries in $H$). The non-degenerate part defines a metric $g$ on the quotient $G/H$. $G/H$ is a homogeneous space, so consider any point $m$ and define its ‘group of symmetries’ $G$ as the subgroup of $O(p)$ that fixes the metric at $m$, i.e. $R^t R = I, R^t g R = g$. So $G$ are orthogonal symmetries of the metric in the tangent space $T_m(G/H)$. By homogeneity, $G$ is independent of the chosen point $m$. Then $G$ coincides with the group of rotation and reflection symmetries of the curved factor of the corresponding ideal rigid body. So the group $G$ consists of symmetries of both the vector boson ‘mass metric’ and the Euclidean metric in the flow domain inhabited by the rigid body. Let us illustrate this equality of symmetry groups in the above examples; the results are summarized in table 1. To identify the group of symmetries in each case, we go to a basis in which the mass metric $g$ at a given point $m$ on $G/H$ is diagonal $g = \text{diag}(\lambda_1, \ldots, \lambda_p)$. The eigenvalues are ordered as

$$0 < \lambda_1 = \cdots = \lambda_{p_1} < \lambda_{p_1+1} = \cdots = \lambda_{p_1+p_2} < \cdots < \lambda_{p-p_r+1} = \cdots = \lambda_p,$$

with $p = p_1 + \cdots + p_r$. Then one checks that the subgroup of $O(p)$ that commutes with $g$ is $O(p_1) \times O(p_2) \times \cdots \times O(p_r)$, with $O(1) = \mathbb{Z}_2$. 


4. The Higgs added-mass correspondence

We now mention some striking analogies between the added-mass effect and the Higgs mechanism. They are summarized in table 2. The rigid body plays the role of gauge bosons—both can gain mass. The fluid plays the role of the scalar field. When the body is accelerated, some energy goes into the flow. Figuratively, the body carries fluid, adding to its mass. Similarly, gauge bosons gain mass by carrying Goldstone modes. The analogy relates the space of fluid flow to the Lie algebra \( G \) (the location of the body provides an origin for the flow domain and it is the space of directions in which the body can move that corresponds to the gauge Lie algebra). The dimension \( d \) of the fluid container \( \mathbb{R}^d \) equals \( \dim G \). The added-mass tensor \( \mu_{ij} \) and the vector boson mass-squared matrix \( M_{ab} \) are both \( d \times d \) matrices. A direction of acceleration relative to the body is equivalent to a direction in \( G \). Zero modes of \( \mu_{ij} \) are directions in which the acceleration reaction force vanishes. These are like directions of residual symmetry in the Lie algebra \( H \). A thin
Consider a bounded rigid body that moves at constant velocity through an infinite, inviscid, incompressible, irrotational potential flow without the formation of vortex sheets, wakes or cavities. It feels no added mass (this is part of d'Alembert’s ‘paradox’ [9]). However, it is incompressible, irrotational potential flow without the formation of vortex sheets, wakes or cavities. Among these rigid bodies there are ‘ideal’ ones, with maximal symmetry group. The identification of $G$ with the space of fluid flow related symmetries of the ‘mass’ metric at any point of $G/H$ to those of the curved factor of the corresponding ideal rigid body (see §3).

We say that a particular SSB pattern corresponds to a particular rigid body if the vector boson masses coincide with the added-mass eigenvalues. The latter do not, generally, determine the body. A sphere and cube of appropriate sizes have identical added-mass eigenvalues, just as we have a massless photon along an unbroken symmetry generator of $G$. In general, the number of flat directions of the body is equal to the number of massless vectors.

We say that a particular SSB pattern corresponds to a particular rigid body if the vector boson masses coincide with the added-mass eigenvalues. The latter do not, generally, determine the body. A sphere and cube of appropriate sizes have identical added-mass eigenvalues, just as appropriate SU(2) and U(1)$^3$ gauge theories share vector boson mass spectra. So the correspondence, at this level, relates a class of classical gauge theories to a family of rigid bodies. Among these rigid bodies there are ‘ideal’ ones, with maximal symmetry group. The identification of $G$ with the space of fluid flow related symmetries of the ‘mass’ metric at any point of $G/H$ to those of the curved factor of the corresponding ideal rigid body (see §3a).

Table 2. The Higgs added-mass correspondence.

<table>
<thead>
<tr>
<th>added-mass effect</th>
<th>Higgs mechanism</th>
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</thead>
<tbody>
<tr>
<td>rigid body</td>
<td>gauge bosons</td>
</tr>
<tr>
<td>fluid</td>
<td>scalar field</td>
</tr>
<tr>
<td>space occupied by fluid</td>
<td>gauge Lie algebra</td>
</tr>
<tr>
<td>dimension of container</td>
<td>dim $G$</td>
</tr>
<tr>
<td>added-mass tensor $\mu_{ij}$</td>
<td>mass matrix $M_{ab}$</td>
</tr>
<tr>
<td>added-mass eigenvalues</td>
<td>vector boson masses</td>
</tr>
<tr>
<td>acceleration along flat face</td>
<td>massless photon</td>
</tr>
<tr>
<td>number of flat directions</td>
<td>dim $H$</td>
</tr>
<tr>
<td>sphere moving in three dimensions</td>
<td>SU(2) $\rightarrow$ (1), doublet</td>
</tr>
<tr>
<td>hollow cylinder in three dimensions</td>
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</tr>
<tr>
<td>broken pressure symmetry</td>
<td>broken gauge symmetry</td>
</tr>
<tr>
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<td>VEV $\langle \phi \rangle$ of Higgs scalar</td>
</tr>
<tr>
<td>$F_i - m a_i = \mu_{ij} a_j$</td>
<td>$-\mathbf{F}^\mu + \partial_\mu F^{\mu\nu} = g^2 \langle \phi \rangle^2 A^\nu$</td>
</tr>
<tr>
<td>b.c. on body surface</td>
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disc accelerated along its surface gains no added mass when moving in a three-dimensional fluid, just as we have a massless photon along an unbroken symmetry generator of $G$. In general, the number of flat directions of the body is equal to the number of massless vectors.

Is there a broken symmetry in the added-mass effect? When a sphere moves uniformly, from (4.1) and Bernoulli’s equation (2.3), the pressure distributions on the front and rear hemispheres are identical. This front–back symmetry is broken upon accelerating the sphere. It is a discrete
analogue of the broken gauge symmetry. Moreover, SSB is caused by a non-zero vacuum expectation value $|\langle \phi \rangle| = \eta$. The density $\rho$ is its counterpart. Both occur as pre-factors in mass matrices ($\mu^\text{sphere}_ij \propto \rho a^3 \delta_{ij}$, $M^\text{SU(2)}_{ab} \propto \eta^2 g^2 \delta_{ab}$) and are exclusively properties of the fluid and scalar field (i.e. not having to do with the rigid body or gauge fields).

Our analogy extends to the dynamical equations of the body ($F_i - ma_i = \mu_j a_j$) and massive vector boson $(-j^\nu + \partial_\mu F^{\mu\nu} = g^2 \eta^2 A^\nu)$. The added mass $\mu_j a_j$ is like the Proca mass. The external force $F_i$ and current $j^\nu$ are both sources in otherwise homogeneous equations. $\partial_\mu F^{\mu\nu} = 0$ is the analogue of $ma_i = 0$: free propagation of electromagnetic waves is like uniform motion of a rigid body. The impenetrable body–fluid boundary condition is analogous to gauge–scalar minimal coupling. Other boundary conditions would correspond to non-minimally coupled scalars.

From the spontaneously broken U(1)$^d$ models of §3, we obtain further analogies. There are three ways to prevent spontaneous gauge symmetry breaking: (i) set the gauge couplings $g_i$ to zero, (ii) make the scalars uncharged ($\eta_{ij} \to 0$) under U(1)$^d$ and (iii) let the scalar vacuum expectation value $\eta \to 0$. Similarly, there are three ways to make the added force/mass vanish: (i) set the acceleration components $a_i = 0$, (ii) shrink the body to a point and (iii) let $\rho \to 0$.

5. Discussion

In this paper, we have proposed a new physical correspondence between the Higgs mechanism in particle physics and the added-mass effect in fluid mechanics. While plasmas and superconductors illustrate the Abelian Higgs model, the Higgs added-mass correspondence provides a non-dissipative hydrodynamic analogy for the fully non-Abelian Higgs mechanism. It encodes a pattern of gauge symmetry breaking in the shape of a rigid body accelerated through fluid. A dictionary relates symmetries and various quantities on either side. By identifying the gauge Lie algebra with the space of fluid flow, and relating added-mass eigenvalues to vector boson masses, we are able to specify when a particular pattern of SSB corresponds to a particular rigid body accelerated through a fluid. Besides possible refinements and generalizations (to compressible (see appendix B) and rotational flows or inclusion of fermion masses), the new viewpoint raises several interesting questions and directions for further research in both fluid mechanics and particle physics. (i) The Higgs is the lightest scalar particle. We conjecture that the fluid analogue is a characteristic fluid mode around an accelerating body, with wavelength comparable to the size of the body (rather than the container). There may be several such modes, which could suggest heavier scalar particles. (ii) Understanding such modes requires extension of the added-mass formalism to flows other than those usually studied in marine hydrodynamics (incompressible potential flow). This would allow for waves around the body that could play the role of the Higgs particle. Perhaps the simplest such flows are compressible potential flow, incompressible flows with vorticity (even in two dimensions) and surface gravity waves in incompressible flow around an accelerated body. Moreover, density fluctuations in compressible flow around a rigid body should be analogous to quantum fluctuations around the scalar vacuum expectation value. Thus the HAM correspondence gives a new viewpoint and impetus to develop techniques to study the added-mass effect in flows other than those studied so far. (iii) We identified a discrete broken symmetry in the added-mass effect. Is there a continuous one, perhaps having to do with Galilean invariance? (iv) The fluid flow affects the rotational inertia of a rigid body, giving it an added inertia tensor. Is there a particle physics analogue consistent with the quantization of angular momentum? For instance, could motion through the scalar medium modify the magnetic moments of particles? (v) The HAM correspondence relates rigid body motion through d-dimensional flows (see appendix A) to SSB of gauge theories with d-dimensional gauge groups. Given the importance and simplifications in the ’t Hooft limit of multi-colour gauge models, one wonders whether there are aspects of these fluid flows that simplify as $d \to \infty$. Could a suitable $d \to \infty$ limit provide a starting point for an approximation method for studying three-dimensional flows? (vi) How is the added mass of a composite body
related to the added masses of its constituents? Correspondingly, can one compute a small
correction to the mass of a hadron from Higgs interactions among a system of quarks (beyond
the Higgs contribution to individual current quark masses)? This would be a small ‘Higgs force’
correction to the mass of the proton in addition to the main contributions from strong and
electromagnetic forces.

Acknowledgements. We thank A. Thyaagaraja, V. V. Sreedhar, K. G. Arun, N. D. Hari Dass, T. R. Ramadas,
A. Laddha, G. Date, G. Rajasekaran and R. Nityananda for useful discussions, and anonymous referees
for suggesting improvements to the manuscript.

Author contributions. This paper is the product of joint work of the two authors.

Funding statement. This work was supported in part by grants from the Infosys Foundation and the Department
of Science and Technology, Govt of India.

Conflict of interests. We have no competing interests.

Appendix A. Added-mass effect in \( d \geq 3 \) dimensions

The HAM correspondence relates spontaneous breaking of a \( d \)-dimensional gauge group \( G \) to the
added-mass effect in \( d \)-dimensional fluids. Since there is no restriction on the dimension of \( G \), our
correspondence requires an extension of the standard added-mass effect \([9,11]\) to flows in \( d \geq 4 \),
which we give here. Consider incompressible potential flow in \( \mathbb{R}^d \) around a simply connected
rigid body moving with velocity \( \mathbf{U}(t) \). We assume that the body executes purely translational
motion and that \( \mathbf{v} \to 0 \) asymptotically. The velocity potential satisfies the Laplace equation
\( \nabla^2 \phi = 0 \) subject to impenetrable boundary conditions on the body surface: \( \mathbf{n} \cdot \nabla \phi = \mathbf{n} \cdot \mathbf{U} \). With
the origin located inside the body, \( \phi \) admits a multipole expansion in terms of Green’s function
for the Laplacian \( \nabla^2 g(r) = \delta^d(r), g(r) = -\left(\Gamma(d/2)/2\pi^{d/2}(d-2)\right)(1/r^{d-2}) \) and its derivatives:

\[
\phi(r) = \frac{c}{r^{d-2}} + c_i \delta_i + c_{ij} \delta_i \delta_j + \ldots.
\]  

(A 1)

As in the Cauchy contour integral formula, the multipole tensor coefficients (which are linear
in \( \mathbf{U} \)) may be expressed as integrals of \( \phi \) and its derivatives over the body surface \( A \),

\[
c = \frac{\Gamma(d/2)}{2\pi^{d/2}(d-2)} \iint_A \mathbf{n} \cdot \nabla \phi(r) \, dA,
\]

\[
c_i = \frac{\Gamma(d/2)}{2\pi^{d/2}(d-2)} \iint_A \left[ (\mathbf{n} \cdot \nabla \phi) r_i - \phi n_i \right] \, dA,
\]

\[
c_{ij} = \frac{\Gamma(d/2)}{2\pi^{d/2}(d-2)} \iint_A \left[ (\mathbf{n} \cdot \nabla \phi) r_i r_j - \phi (n_i r_j + n_j r_i) \right] \, dA, \ldots.
\]  

(A 2)

For incompressible flow without sources, the monopole coefficient \( c \equiv 0 \). As in the three-
dimensional case, the impenetrable boundary condition constrains \( \phi \) to be linear in \( \mathbf{U} \),
which allows us to write it as \( \phi = \mathbf{U} \cdot \mathbf{r} \). The potential vector field \( \mathbf{F}(r, t) = \mathbf{F}(r - \mathbf{r}_0(t)) \) is independent
of \( \mathbf{r}_0(t) \) is a convenient reference point fixed in the body. As in \( \S 2 \), we use Bernoulli’s equation
(2.23) to write the pressure–force on the body surface \( A \) in terms of \( \phi \), and use the factorization \( \phi = \mathbf{U} \cdot \mathbf{r} \)
to write the force as the sum of an acceleration reaction \( \mathbf{G} \) and a non-acceleration force \( \mathbf{G}' \), as in
(2.5). From the multipole expansion \( \phi \sim 1/r^{d-1} \) and it follows that \( \mathbf{G}' \) vanishes when the flow
domain is all of \( \mathbb{R}^d \). Thus, we get the same formula (as in three dimensions) for the added-mass
tensor \( \mu_{ij} \) from the acceleration–reaction force:

\[
G_i = \rho \dot{U}_j \int_A F_i n_i \, dA \equiv -\mu_{ij} \dot{U}_j \quad \Rightarrow \quad \mu_{ij} = -\rho \int_A F_i n_i \, dA.
\]  

(A 3)

Despite appearances, \( \mu_{ij} \) only depends on the dipole term in \( \phi \). The linearity of the boundary
condition in \( \mathbf{U} \) implies that \( c_i = d_{ij} U_j \) is linear in \( \mathbf{U} \). The constant source doublet/dipole tensor \( d_{ij} \)
depends only on the shape of the body. Using equation (A 2) for \( c_i \) and the boundary condition on the surface, we obtain

\[
c_i = d_{ij} U_j = \frac{\Gamma(d/2)}{2(d-2)\pi^{d/2}} \int_A \{ (n \cdot U) r_i - \phi n_i \} dA
\]

\[
e = \frac{\Gamma(d/2)}{2(d-2)\pi^{d/2}} \int_{\text{body}} \delta r_i \ dV - \frac{\Gamma(d/2)}{2(d-2)\pi^{d/2}} \int_A \left[ V_{\text{body}} \delta_{ij} + \frac{\mu_{ij}}{\rho} \right] U_j. \tag{A 4}
\]

Since this is valid for any velocity \( U \), we arrive at a relation between \( \mu_{ij} \) and the dipole tensor

\[
\mu_{ij} = \rho \left[ \frac{2(d-2)\pi^{d/2}}{\Gamma(d/2)} \delta_{ij} - V_{\text{body}} \delta_{ij} \right]. \tag{A 5}
\]

This expression for \( \mu_{ij} \) shows that it only depends on the dipole part of \( \phi \). It does not involve integrals and gives a simple way of computing \( \mu_{ij} \) once the dipole term in \( \phi \) is known. Let us illustrate this with the example of a \((d-1)\)-dimensional sphere \( S^{d-1}_a \) of radius \( a \), moving through fluid in \( \mathbb{R}^d \). A moving sphere instantaneously centred at the origin induces a dipole flow field with potential \( \phi = c_i \partial_i r_{2-d} = -(d-2)r^{-d} c \cdot r \). The multipole tensors \( c_{ij}, c_{ijk}, \ldots \) are constant tensors of rank \( > 1 \), linear in \( U \). Spherical symmetry of the body denies us any other vector/tensor from which to construct them, so they must vanish. The dipole coefficient \( c \) may be self-consistently determined by inserting this formula for \( \phi \) in (A 2). One obtains

\[
c_i = \frac{a^d}{(d-1)(d-2)} U_i \quad \text{or} \quad d_{ij} = \frac{a^d}{(d-1)(d-2)} \delta_{ij}. \tag{A 6}
\]

Hence, the added-mass tensor for a \((d-1)\)-sphere of radius \( a \) moving in \( \mathbb{R}^d \) is

\[
\mu_{ij}^{\text{sphere}} = \rho \frac{2\pi^{d/2}a^d}{d(d-1)\Gamma(d/2)} \delta_{ij} = \frac{\text{(mass of fluid displaced)}}{(d-1)} \delta_{ij}. \tag{A 7}
\]

This reduces to the well-known results for planar or three-dimensional flow around a disc or 2-sphere. In §5, we speculate on the possible relevance of a suitable \( d \to \infty \) limit.

### Appendix B. Added-mass effect for compressible potential flow

Treatments of the added-mass effect assume for simplicity that the flow is inviscid, incompressible and irrotational. However, physically, it is clear that the effect is present even in compressible or rotational flow. Indeed, according to our correspondence, density fluctuations around incompressible flow should correspond to quantum fluctuations around a constant vacuum expectation value for the scalar field. Moreover, to look for a fluid analogue of the Higgs particle, i.e. a ‘Higgs wave’ around an accelerated rigid body, we need a generalization of the added-mass effect to compressible flow. As is well known, the resulting flows can be very complicated. Here we take a small step by formulating the added-mass effect for compressible potential flow around a rigid body executing purely translational motion at velocity \( U(t) \). We assume the flow is isentropic so that \( \nabla p/\rho = \nabla h \), where \( h \) is specific enthalpy. Euler’s equation \( \partial v/\partial t + v \cdot \nabla v = -\nabla h \) then implies an unsteady Bernoulli equation for the velocity potential \( \phi \),

\[
\partial_t \phi + (\frac{1}{2}) v^2 + h = \text{const.}(t). \tag{B1}
\]

For concreteness, we consider adiabatic motion of an ideal gas so that \( p/p_0 = (\rho/\rho_0)^\gamma \), where \( \gamma = c_p/c_v \) is the adiabatic index and \( p_0, \rho_0 \) are reference pressure and density. Then \( h = (\gamma/(\gamma - 1))p/\rho \). Of course, \( \phi \) and \( \rho \) are to be determined by solving the Euler and continuity equations subject to
initial and boundary conditions. To identify the added force on the body, it helps to regard the continuity equation and impenetrable boundary conditions on the body, namely

\[(\nabla \rho \cdot \nabla + \rho \nabla^2)\phi = -\partial_t \rho \quad \text{and} \quad \hat{n} \cdot \nabla \phi = \hat{n} \cdot \mathbf{U}, \quad (B2)\]

as a system of inhomogeneous linear equations for \(\phi\) given \(\rho\) and \(\mathbf{U}\). The r.h.s. of this system is linear in \(\mathbf{U}\) (and \(\rho\)), so, formally, the solution of this equation can be expressed as \(\phi = \mathbf{U} \cdot \mathbf{\Phi}(r, t) + \psi(r, t)\) where the potential vector field \(\mathbf{\Phi}\) and the supplementary potential \(\psi\) are \(\mathbf{U}\)-independent but depend on \(\rho\). To see why this is true, discretize the system as a matrix equation \(A(\rho)\phi = b\). The upper rows of the matrix \(A\) encode the operator \(\nabla \rho \cdot \nabla + \rho \nabla^2\) while the lower rows encode \(\hat{n} \cdot \nabla\). The upper rows of the column vector \(b\) represent \(-\partial_t \rho\) and the lower rows contain \(\hat{n} \cdot \mathbf{U}\), so that we may write \(b = b_1(\rho) + b_2(\mathbf{U})\), where \(b_2\) is linear in \(\mathbf{U}\). Inverting \(A\) gives the desired decomposition.

With the aid of Bernoulli’s equation, the force on the body \(-\int_A \rho \hat{n} \cdot dA\) becomes

\[F_i = \left(\frac{\gamma - 1}{\gamma}\right) \int_A \rho \left[ \partial_t \phi + \frac{1}{2} \nabla^2 - \text{const}(t) \right] n_i \, dA. \quad (B3)\]

Using our factorization \(\phi = \mathbf{U} \cdot \mathbf{\Phi} + \psi\), the force on the body is the sum of an acceleration reaction force \(G_i = -\mu_{ij} \mathbf{U}_j\) and a non-acceleration force \(G_i'\):

\[G_i = \left(\frac{\gamma - 1}{\gamma}\right) \mathbf{U}_j \int_A \rho \mathbf{\Phi} n_i \, dA \quad \text{and} \quad G_i' = \frac{\gamma - 1}{\gamma} \int_A \rho \left[ \mathbf{U}_j \mathbf{\Phi}_j + \psi + \nabla^2 - \text{const}(t) \right] n_i \, dA. \quad (B4)\]

The added-mass tensor \(\mu_{ij} = -(\gamma - 1) / \gamma \int_A \rho \mathbf{\Phi} n_i n_j \, dA\). To find \(\mu_{ij}\) for a given body, we need to solve for \(\rho\) and \(\mathbf{v}\) using the equations of motion. Unlike for constant density, where \(\mu_{ij}\) is constant, here it could change with time and location owing to density variations arising from the acceleration of the body. Corrections to the added mass owing to density fluctuations are analogous to corrections to the \(W\) and \(Z\) boson masses owing to quantum fluctuations around a constant scalar vacuum expectation value. This interesting phenomenon will be further investigated elsewhere.

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