The dynamics of Wave Carpet – A novel deep water wave energy design

Paul Mario Koola, Akif Ibragimov
KBSI
One KBSI Place, 1408 East University Drive
College Station, Texas, 77840, USA
pkoola@kbsi.com

***Abstract* - Wave Carpet is a novel deep offshore wave-power floating system concept funded by the Office of Naval Research that will have low overall life cycle cost due to an integrated design and be rapidly re-deployable. In this paper we numerically model the Wave Carpet motion using a coupled hydro-elastic time-domain solution. The problem is resolved by the finite element method in two-dimensions with certain restrictions on the initial distribution of the potential function. Typical results of the geometrical and physical parameters on energy distribution along the carpet are presented.**

I. INTRODUCTION

Solar radiation on the earth estimated to be about 10^{16} Watts is continuous and inexhaustible. The oceans, which covers about 70% of the earth's surface acts as a natural reservoir for this energy source. Solar radiation on the earth's surface creates pressure gradients in the atmosphere, which give rise to winds, which blow over the ocean water mass to create waves. In order to design wave energy devices it is essential to understand the nature of these water waves, and the operation of these devices at sea. In this paper we will discuss the main issues and problems facing wave energy absorption from a standpoint of deep-water rapidly redeployable steady power wave energy design.

Wave Carpet is a novel deep offshore wave-power floating system concept funded by the Office of Naval Research that will have low overall life cycle cost due to an integrated design. Unlike earlier wave power designs one of the major requirements is that this device has to be rapidly re-deployable. This device should be easier to maintain and must operate in deep water away from the mainland electric grid.

A. *Device Designs:*

Three main categories of phenomenon can be utilized in wave energy conversion systems. [1]

1. Surface wave height or slope variations
2. Subsurface water particle movement or variations in pressure and
3. Wave transformation when approaching natural or artificial shoals.

Most of the devices invented so far, including the most promising systems, seem to belong to the first category. These include various types of wave-actuated buoys, oscillating bodies or bodies in which the waves cause pneumatic pressure variations. The devices in the second group have to face an exponentially decaying wave energy level below the surface. The investigations under the third category are site specific and have been very rare.

Another important categorization is based on the dimensions of the device compared to the wave and its orientation with respect to the wave. [2] They are the Terminator, Attenuator and Point Absorber. A terminator is a device that is aligned parallel to the wave front and perpendicular to the principal wave direction, thus terminating the waves. An attenuator lies in the principal wave direction and attenuates the waves as it passes by. A point absorber is a small device in plan compared to the wavelength. These devices can diffract the waves thereby capturing energy from a width greater than its own dimensions.

From a functional perspective devices can be categorized as dynamic and passive. In dynamic systems, one element of the system is tuned into excitation by the waves and can be optimized to extract maximum energy through proper tuning of system characteristics. Most of the popular devices fall under this category and some examples are the Cockerell Raft, Salter's Duck, Bristol cylinder, floating pistons and platforms and devices with oscillating water column. In passive systems there is not much possibility of tuning and examples include the TAPCHAN system [3], which uses a ramp to run up waves into a reservoir. These types of systems are highly site specific.

While it will be impossible to describe all these systems here what will be more useful is to analyze some of the drawbacks of these systems with a view to improve future designs. Some of the main problems encountered with sea trials of these devices are:

- Hinges and components exposed to the sea are highly susceptible to corrosion. Moving components under water are extremely difficult to maintain.
- Train of adjacent floating devices requires accurate positioning techniques especially in extreme weather.
- Power is the product of force and velocity. Wave power is associated with very large forces but relatively low velocities. Design of components need to keep this enormous forces in mind.
- Wave Power is irregular and varies at different time scales: instantaneously, daily, monthly or seasonal. Storage at different time scales is critical to a deep-water design far away from the mainland electric grid.

Due to the above mentioned problems and the Navy requirements of rapid deployability and redeployability from site to site under all weather and operational conditions we present Wave Carpet as a novel concept design that could meet these added requirements.

II. OVERVIEW OF THE PROPOSED SOLUTION

Our solution the Wave Carpet is a concept for the design of an ocean wave energy power plant in deep water with depths greater than 100 meters. This Carpet design is modular for mass production. The expected rated steady electric power output will be in the range of 10 MW depending on the site and size of the power plant.

A. *Design Philosophy*

Our design philosophy is to develop a cost effective design for the entire life cycle of the power plant rather than just an efficient power absorption device. To achieve this we reverse design the power plant from conventional practice. What is the total Life Cycle Cost of a wave energy device? The Total Life Cycle (ownership) Cost for a wave energy device can be broken down into

- The Hull or Structure
- Power Take Off System
- Mooring and Anchors or dynamic positioning
- Electrical Transmission
- Maintenance
- Miscellaneous

From a systems perspective it is the total cost of all these components over the entire life of the system that has to be optimized. Another view of cost is from a device efficiency perspective. A good rule of thumb is that increasing the efficiency of the device is at the cost of power produced. This is because the rate at which efficiency increases close to the theoretical maximum limit is accompanied by a disproportionately steeper increase in cost to achieve those efficiencies. A lesson to be learnt from this is that it might be wiser to let go off some of the energy available to be successful in the long run. Waves are free and it sometimes is more expensive to capture them than to let them go. Hence as is usual with nature a compromise is the best solution.

Offshore maintenance in general is expensive and for the cockerel raft wave energy device it was estimated to be about 22% of the total cost of the power produced. [4] Independently Taylor [5] also confirmed that maintenance has a first order effect on the cost of wave energy produced. Increasing the maintainability of the device is hence highly critical to a successful overall design.

As mentioned earlier depending on the time window the variability of wave power changes. Large variations of 1000 % across seasons are not uncommon. Hence energy storage is very critical.

B. *The Concept – "Wave Carpet"*

Long ago sailors had a practice of letting go of their fuel into the ocean to calm stormy seas. [6] [7] [8] The Wave Carpet will be the modern day equivalent of the old-fashioned wave damper. It could be thought off as a flexible rubber mat square kilometers in size. Like the oil that spreads out around the ship protecting it, the wave carpet will spread out in all directions and be extremely large in dimensions by today's offshore standards. It will be a cross breed between a terminator and an attenuator (a termenuator) and will be just the opposite of the point absorber. Its size will be comparably larger than the largest wavelengths encountered making it a very large floating structure (VLFS). Current technologies of similar proportions are the Mobile Offshore Bases (MOB) being built for the US Navy and the Japanese seaports. The sheer size of the structure will provide the reaction required to oppose waves, since different ends of the structure will be subjected to nearly non synchronized loads due to phase differences of the wave at different regions. This should help simplify position keeping. An artist's impression of the wave carpet is shown Fig. 1

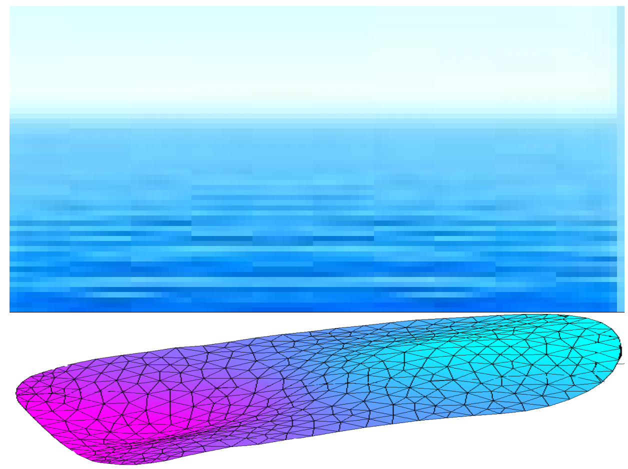

Fig. 1: The "Wave Carpet"

The wave carpet design is better favored as it is a monolithic block without these mooring line problems. The biggest benefit of the wave carpet is at deployment where due to its monolithic structure once towed and deployed in position there is comparatively less work to start the plant. Also redeployment to another site is only a matter of towing using tugs.

Another advantage with this design is that in deep waters most devices are incapable of absorbing from multidirectional short crested seas. The Wave Carpet does not have any preferred direction or orientation, as it will be designed to absorb from any direction. The wave slowly but effectively though not necessarily efficiently will be eaten up by the Wave Carpet.

The wave carpet will be constructed out of reinforced rubber [9] as has been tested in the Calm wave energy converters. This will almost eliminate corrosion. Unlike the Calm the wave carpet design will not have excessively large membrane deflections and hence will have life exceeding the multimillion buckle free operations that will typically be encountered. Also like most wave energy designs that have a 15 to 20 year design life, the wave carpet will be designed for a 15-year life. The cheaper cost of the wave carpet will still maintain effective cost economics. Also these carpets can be downgraded in power rating after sufficient years in deep sea to be brought closer to shore or island communities to deliver cheap power. The capital cost of the carpet would already be expensed by this time. This concept is similar to downgrading fighter jet turbine engines and using them for secondary power plants.

The specifics of the power take off mechanism are not so very critical to the benefits of the overall design. Some possible power take off mechanisms include piezoelectric materials or dielectric polymers for direct mechanical to electric conversion.

We present our ideas on how we could integrate the carpet with distributed small power take off devices. Our intention is that we could plug devices into the carpet as technology progresses. Fig. 2 shows the general schematic of power conversion from Wave to Wire or Electricity.

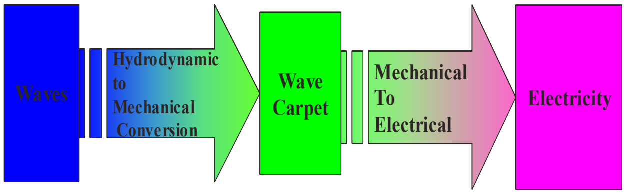

Fig. 2: Wave to Wire System Chain

III. Modeling of Wave Carpet Dynamics

In this section we develop a coupled hydro-elastic time-domain solution for wave generation and carpet motion in a tank. The numerical tank concept for wave modeling has received considerable attention in the past few years. [10][11] We adopt the concept to the numerical tank simulation of transient motion of the Wave Carpet.

We formulate the problem in the Cartesian coordinate system (x,y,z) with 'x' the direction of wave propagation and along the free surface, 'y' along the width of the carpet and 'z' the vertical direction positive upwards. (Fig. 3) Let S2 be the surface of the tank lying under the "carpet" and S6 the remaining free surface on the top of the tank. Let 't' be the time dimension.

Assume that thickness of the carpet is ignored and $w(x,y,t)$ is the deflection of the carpet. We assume an inviscid, incompressible and irrotational flow described by a velocity potential $\Phi(x,y,z,t)$ satisfying the Laplace equation in the domain.

$$\nabla^2\Phi(x,y,z,t) = 0 \quad in \quad 0 < x < L_x; 0 < y < L_y; -d < z < 0 \qquad (1)$$

With the following boundary conditions:

$$\Phi_z\Big|_{z=-d} = \frac{\partial\Phi}{\partial z}\Big|_{z=-d} = 0 \quad and \quad \Phi_y\Big|_{y=0,Ly} = \frac{\partial\Phi}{\partial y}\Big|_{y=0,Ly} = 0 \qquad (2)$$

First equation in (2) is a non-flow condition at the bottom $z=-d$. Second symmetry (isolation) condition in (2) is at the sidewalls of the tank $y=0, y=Ly$.

The combined free surface boundary condition in areas not covered by the carpet is given by,

$$\Phi_z = -(1/g)\frac{\partial^2\Phi}{\partial t^2} \quad when \quad z=0 \quad and \quad (x,y)\in S6 \qquad (3)$$

The carpet is modeled as an elastic beam characterized by its length L, width Ly, stiffness D, damping c, mass m and density ρ. We assume that the carpet behavior is subjected to Timoshenko-Euler equations [12]. For energy extraction we introduce a damping term.

$$m\frac{\partial^2 w}{\partial t^2} + c\frac{\partial w}{\partial t} + D\Delta^2 w + \rho g w + \rho\frac{\partial\Phi(x,y,0)}{\partial t} = 0$$

$$when \ z=0, (x,y)\in S6 \qquad (4)$$

The left side of (4) is the sum of the total force on the carpet, plus resistance by virtue of the energy extraction, plus shear forces and momentum appearing in the bending carpet, plus gravity force.

The conjugate condition between water surface and the carpet floating above is given by,

$$\Phi_z = -\frac{\partial w}{\partial t} \quad when \quad z=0 \quad and \quad (x,y)\in S7-(area \ \ covered \ \ by \ \ carpet) \qquad (5)$$

On the edge of the carpet is a free of stress condition,

$$\frac{\partial^2 w}{\partial n^2} + \nu\frac{\partial^2 w}{\partial\tau^2} = 0, \quad and$$

$$\frac{\partial^3 w}{\partial n^3} + (2-\nu)\frac{\partial^3 w}{\partial\tau^2\partial n} = 0 \qquad (6)$$

$$on \quad the \quad S7-carpet \quad edges$$

Here τ and n are the tangent and normal to the carpet's boundary.

In addition we assume that on the left boundary at x = 0 a wave maker generates periodical waves. In general waves can be generated in two ways [10]

- By prescribing wave maker motion on the upstream boundary
- By specifying wave behavior on controlled boundary

First approach in general is ill posed and could lead to numerical instability of the solution of the problem in time varying domain. The second approach mathematically is well posed and allows simulation using time dependent boundary condition on the controlled boundary. Both approaches are mutually bounded and often can be reduced to each other, but we will use the latter. Hence the wave maker is modeled using properties of standard wave forms like a certain velocity distribution f0(y, z, t).

$$\frac{\partial\Phi}{\partial x}\Big|_{x=0} = f_0(y,z,t) \quad on \ S1 \qquad (7)$$

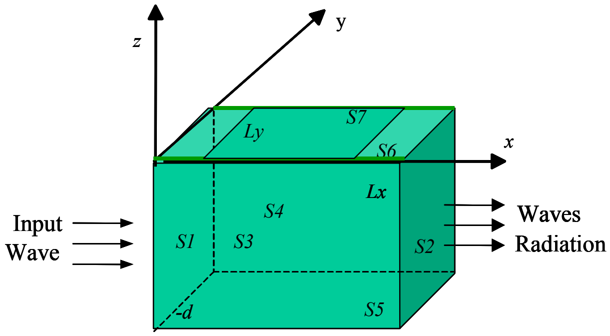

Fig. 3: Scheme of tank (S1- boundary on which waves are generated, S2 - boundary subjected to radiation condition, S3, S4 (sides of the tank y=0 and y=Ly) subjected to non flow condition, S5 (tank's bottom) subjected to non-flow condition, S7 (carpet) subjected to equation (4), S6 (surface of the tank free from the carpet) subjected to equation (3).

To satisfy a finite computational domain on the right side boundary x = Lx the flow satisfies the Sommerfeld radiation condition ensuring that the waves are outgoing [13][14]. One approach for imposing Sommerfeld's radiation condition in a bounded reservoir was first developed by Orlanski [13] In the present work we use a modified Orlanski equation for wave radiation condition modeling on the boundary associated with infinity and is represented by,

$$\frac{\partial \Phi}{\partial x} = -\frac{1}{c}\frac{\partial \Phi}{\partial t} \quad when \quad x = L_x \quad on\ S1 \tag{8}$$

This implies numerical computation of the phase velocity 'c': This representation guarantees a stable and unique solution of the corresponding equations, and also prevents the possible impact of the artificial boundary on the carpet/wave behavior.

Sides y = 0 and y = Ly are tank walls and we impose the non-flow condition in y direction on the S3 and S4

$$\left.\frac{\partial \Phi}{\partial y}\right|_{y=0,L_y} = 0 \tag{9}$$

The Initial condition is,

$$\Phi(x, y, z, 0) = h(x, y, z) \tag{10}$$

Equations (1) to (10) define the coupled hydro-elastic time-domain solution for wave generation and carpet motion in a tank. In this paper we have resolved the problem by applying finite element method in two-dimensions with a certain restriction on the initial function h (x, 0, z). The two dependent variables w(x,t) and $\Phi(x,0,t)$ are coupled by conjugate condition (5) and through (4).

Next we present typical results from our numerical simulations. Our focus was to understand the response of the carpet for different damping values (c) and material properties like density (ρ) and stiffness (D). We define Response as Displacement of the free surface per unit Wave Amplitude.

Fig. 4 is the Time Response of the free surface of the tank for c =1000, ρ = 0.01. The free surface is spatially represented as Distance / Carpet Length with the incoming wave (from 0 to 1), carpet (from 1 to 2) and outgoing wave (from 2 to 3). Hence the wavelength and carpet length are equal.

Multiple solutions are over plotted for different time steps. The time steps are chosen to coincide with the input wave period of 0.8 seconds. The first four time steps are essentially transient. Response at step number five and six are already close to each other. Time 5.7 is step number eight and is presented to illustrate the steady state behavior. At steady state, the response in front of the carpet at the wave maker (x =0) is almost unity whereas behind the carpet it dies down to a very low value. The carpet has absorbed the energy in the wave thereby reducing wave transmission.

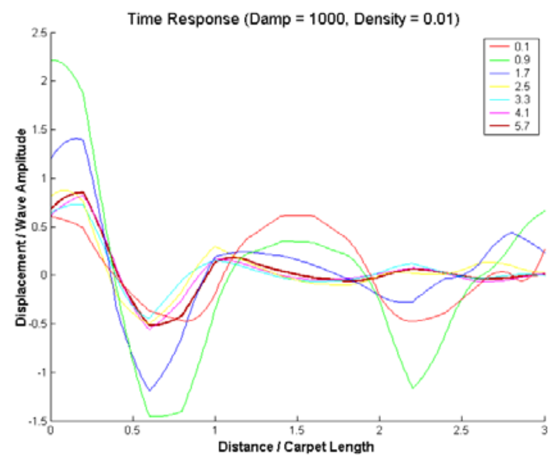

Fig. 4: Time Response [c = 1000, ρ = 0.01]

Fig. 5 shows the displacement at steady state for [c = 1000, ρ = 0.01]. The water depth is taken equal to the carpet length. The absorption of the carpet is clearer in this figure.

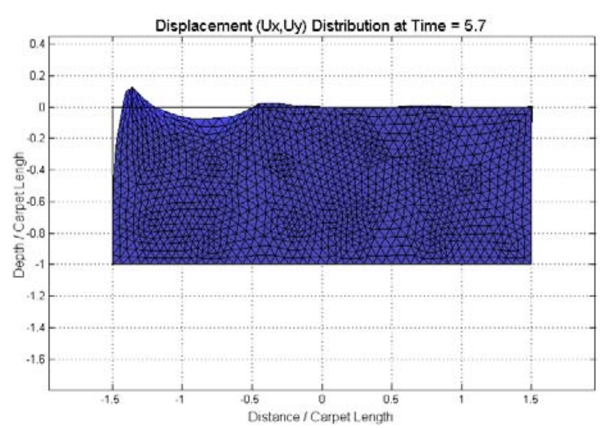

Fig. 5: Steady State Displacement [c = 1000, ρ = 0.01]

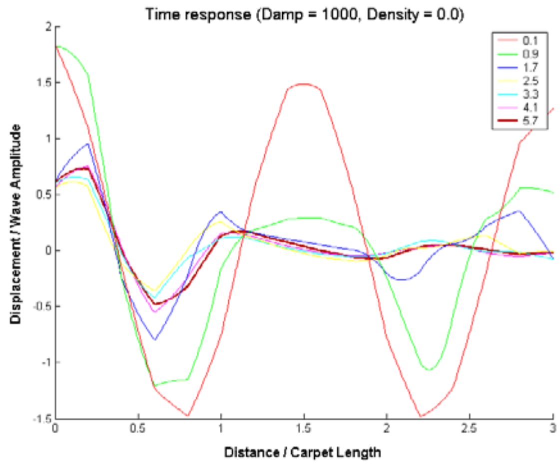

Fig. 6: Time Response [c = 1000, ρ = 0]

Fig. 6 shows the time response as in Fig. 4 but for ρ = 0. This change in density only affects the transient response; the steady state solution looks similar at time step 5.7.

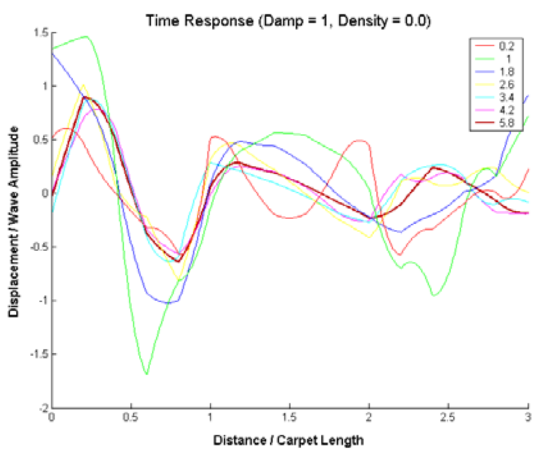

Fig. 7: Time Response [c = 1, ρ = 0]

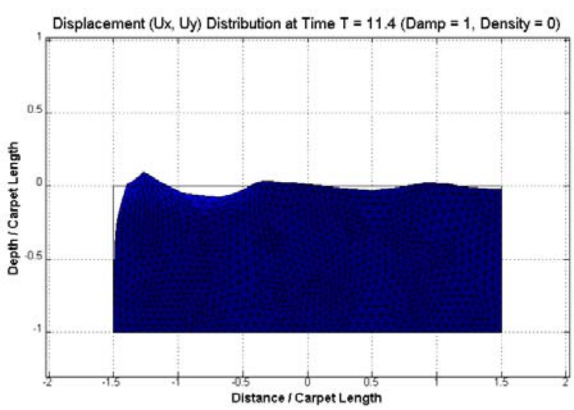

Fig. 8: Steady State Displacement [c = 1, ρ = 0]

Fig. 7 shows the response at damping c=1 and density zero. The low damping causes substantial portion of the wave to pass through the carpet as compared to Fig. 4 and Fig. 5 with high damping. Fig. 8 shows the steady state solution for this low damping case and when compared to Fig. 5 we can see the difference of carpet absorption.

IV. CONCLUSIONS

This paper presents a new deep-water wave energy device the Wave Carpet. Based on a review of past work we discuss the main issues that would be critical for such a deep-water rapidly redeployable design. We then conceptually introduce the wave carpet as a feasible solution.

We then propose a theory to model the carpet using the Numerical Wave Tank Concept and formulate the coupled hydro-elastic time-domain solution for wave generation and carpet motion in a tank. We then solve this problem using Finite Element Methods in two dimensions and present typical results.

Acknowledgments

Our special thanks to Dr. Richard Mayer, President KBSI for his enthusiasm, encouragement and support. Part of this work was sponsored by the Office of Naval Research under SBIR contract No. N00014-02-M-0147 titled "Wave Carpet".

References

[1]. Glendenning, I, "Energy from the Waves", Proceedings of the Oceanology Intl.78, Brighton, Technical session L, Energy from the seas, pp 20-32, 1978.

[2]. ETSU, "Wave Energy, The Dept of Energy's (UK) R&D Programme 1974-198, ETSU R26, March 1985.

[3]. Newham, M. "Norway starts up world's first commercial wave power plants", Solar Energy Intelliegence report, Jan 21, p24, 1986.

[4]. Wolley, M.V., Tricklebank, A.H., "Mass production of concrete wave energy devices", The Structural Engineer, 59A, 2, 57-68, 1981.

[5]. Taylor, R. J., "Wave Energy: the influence of maintenance / repair requirements", Second Intl. Symposium on Wave and Tidal Energy, University of Cambridge, England. 1981.

[6]. Lamb, Horace, "Hydrodynamics" New York Dover Publications. (6th Ed page 631-632), 1945.

[7]. Reynolds. "On the effect of Oil in destroying Waves on the surface of Water" Brit. Ass. Rep. 1880 [papers, i. 409]

[8]. Aitken. "On the effect of Oil on a stormy sea", Proc. Royal Soc. Edin. xii, 56, 1883

[9]. Duckers, L.J. "Reinforced Rubber membranes for the Calm Wave Energy Converter" The Proceedings of the ninth International Offshore and Polar Conference, Brest, France, 1999.

[10]. Baudic S.F. Williams A.N., Kareem A., A two-Dimensional Numerical Wave Flume, Transaction of AME, Vol. 123, May, 70-74, 2001.

[11]. Shaffer. H. A. Second Order Wave-Maker Theory For Irregular Waves", Ocean Eng., 23, pp 47-88.

[12]. Andrianov A., Hermans A. A VLFP on Infinite, Finite and Shallow Water, 17-th International workshop on water waves and floating bodies,Cambridge,UK, April 14 - 17, 2002.http://www.wsatkins.com/17iwwwfb/proceedings.

[13]. Orlanski, A simple Boundary for Unbounded Hyperbolic Flows, J.Comp. Phys., 21, pp 251-269, 1976.

[14]. Bengquist B, Majda A., Absorbing Boundary Conditions for Numerical Simulation of Waves Mathematics of Computation, V. 31, N0 139, July 1977.